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Washington, D.C.
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ABSTRACT

The purpose of the HMT Study was to develop and demonstrate a systematic methodology for identifying and evaluating innovative technology concepts offering revolutionary, breakthrough-type capabilities for advanced space missions and for assessing their potential mission impact. The methodology is based on identifying the new functional, operational and technology capabilities needed by hypothetical "Horizon" space missions that have performance requirements that cannot be met, even by extrapolating known space technologies. Nineteen Horizon Missions were selected to represent a collective vision of advanced space missions of the mid-21st century. The missions typically would occur beyond the lifetime of current or planned space assets. The HM methodology and supporting data base may be used for advanced technology planning, advanced mission planning and multidisciplinary studies and analyses.

INTRODUCTION

All space missions are fundamentally limited by technology. Whether in terms of scope, allowable operations, performance, timetable or cost, technology underlies nearly all constraints on a mission, with the exception of some human physiological requirements. Furthermore, ongoing technological research and development typically results in only incremental increases in future performance. Thus, future missions can be expected to attain mostly evolutionary improvements in space capabilities.

However, opportunities to make revolutionary improvements do exist—in the form of high payoff, highly innovative, high risk ("breakthrough-type") technology concepts and approaches. "Breakthrough" technologies offer the chance to jump over or completely bypass the limitations of current technologies. In fact, any hoped-for era of very low cost space operations, rapid and frequent solar system flights, and large-scale workday presence in space will likely depend on breakthroughs in technology. These concepts and approaches may come from new space technology ideas, emerging non-space technology frontiers, or new scientific discoveries.

The purpose of this study was to develop and demonstrate a systematic methodology for identifying and evaluating innovative technology concepts offering revolutionary, breakthrough-type capabilities for advanced space missions and for assessing their potential mission impact. The HM methodology thus provides an analytical tool that enables the systematic evaluation of high payoff, high risk technology ideas to be introduced into advanced space technology and mission planning. The methodology is based on identifying the new functional, operational and technology capabilities needed by hypothetical "Horizon" space missions that have performance requirements that cannot be met, even by extrapolating known space technologies.

Horizon Missions (HM) serve as an artifice to focus thinking on new space functional elements and operational relationships and consequently on new technology frontiers and functions. By eliminating extrapolation, HM performance requirements force conceptual thinking toward innovative, even radical, new functions and capabilities and away from simple projections and variations of existing functions and capabilities.

Nineteen Horizon Missions were selected to represent a collective vision of advanced space missions of the 21st century. The missions typically would occur beyond the lifetime of current or planned space assets. In particular, they lie beyond 2020, the end of the projected period of the proposed lunar and Mars missions of the U.S. Space Exploration Initiative. All of these Horizon Missions have been described in the literature.

This methodology along with its supporting data base could be used for three specific forms of advanced study and analysis: advanced technology planning, advanced mission planning and multidisciplinary system studies. The detailed methodology and analysis of the HMT Study are described in "Horizon Missions - Technology Concept Study: Volume 1" (Ref. 1). A compilation of the descriptions of the Horizon Missions and a bibliography of over 350 references to the 19 missions are provided in "Horizon Missions - Hypothetical Space Missions of the 21st Century: Volume 2" (Ref. 2).
BACKGROUND

The scope and intent of the HMT Study can be further understood by contrasting it with previous space technology assessments conducted by NASA over the past two decades. The "Outlook for Space" Study (Ref. 3) and the NASA Space Systems Technology Model (NSSTM) (Ref. 4) examined future technology options based either on extrapolations of current technologies or on projected technologies required by currently "endorsed" space mission programs. The NSSTM also did identify but did not examine areas of "technology opportunity", one class of which could revolutionize spaceflight activities. Only the Forum for Speculative Technology (Ref. 5) tried to look beyond the narrow, "tunnel" perspectives dictated by technology extrapolation. In comparison, the specific intent of the HMT Study is to devise a systematic means of identifying and evaluating new "breakthrough" technology options or research opportunities based on space missions with performance requirements that cannot be met even with extrapolated technologies.

For valid reasons most space technology efforts result in only incremental increases in performance. But if the history of technology is any lesson, space technology will have its own breakthroughs. These will open the door to revolutionary new capabilities in space, including order-of-magnitude increases in performance, new instruments and operations, and previously unallowed functions, objectives and missions. But against these exciting visions of our space future, the sheer novelty and significant uncertainty of breakthrough concepts create their own obstacle to being incorporated into advanced technology and mission plans.

Thus the technology options that could provide the greatest enhancement of future space operations and exploration face the greatest hazards to being adequately pursued.

The extremely high leverage that breakthrough technology concepts have on future missions should be accounted for in advanced mission and technology planning and analysis. The HM methodology has been developed for this purpose.

HORIZON MISSIONS

Horizon Missions are simply defined – they are hypothetical space missions that have performance requirements that cannot be met even with extrapolations of known space technology. This "extreme" performance requirement is necessary to be able to stimulate technology ideas outside the natural tendency to simply extrapolate current capabilities. Furthermore, in order to have a reference case of a conventional technology approach, the HMs were selected from those proposed in the literature. And partly for the same reason, missions or spacecraft that have been proposed as predominantly a showcase for new technology insights were not selected as HMs.

The identification and selection of the HMs involved an extensive literature survey, which is provided in Reference 2. Nineteen (19) HMs were chosen, most of which would occur beyond the lifetime of current or planned space assets. A graphical depiction of the "Horizon Missions" is shown in Figure 1. The figure shows a wide range of very advanced space missions that could be carried out in the 21st century. They are grouped into five representative categories: interstellar, asteroid belt, outer solar system, space communities and response missions. Conspicuously absent is a category for unmanned earth-orbiting spacecraft. As with the HMs, the categories were chosen to enable a break from current space mission categories in order to facilitate more innovative thinking about alternative engineering approaches and new technology functions.

The HMs are bounded on one side by planned or proposed missions that can be enabled through the extrapolation of current technologies. Basically, the technologies required for them are within sight - they exist or can be developed from planned technology activities. These Extrapolatable Missions include the manned lunar and Mars missions that are projected to be achievable by the 2000-2020 period (Ref. 6). On the other side fall Over-the-Horizon Missions - their scale is so vast or driving motivation so far culturally from the present that it is difficult to engage a serious consideration of their real technology requirements.

The HMs fit into a time perhaps 30-100 years from now in which all the current space science and exploration objectives have been met and the nation will have an even grander vision and presence in space. In one sense they provide a collective vision of space missions of the 21st century.

DESCRIPTION OF METHODOLOGY

The essence of the HM methodology is to define a future mission capability, and then, "looking backward from the future" determine the functional, operational and technological capabilities needed to enable it. The HMs are chosen to be beyond any
extrapolated technology or projected space assets to facilitate determination of their functional requirements independently of technology availability. By arresting the natural tendency to plan based on currently feasible or projected-feasible technologies and engineering solutions, HMs force creative thinking about new technology frontiers and new technological functions manifested by recent scientific discoveries. They provide a framework from which to identify precursor technology events ("technology seeds") that could be progenitors to future space technology systems of radically different properties and applications.

The four steps of this Horizon Mission methodology are shown in Figure 2. In Step 1 a mission is selected having a scope and objectives beyond extrapolated capabilities. In Step 2 the mission function, operational and performance requirements are identified. Insofar as possible, the full descriptions of the HMs used in this study were taken directly from the literature. The HMs thus reflect the normal extrapolative technology thinking associated with advanced mission planning.

Initially, the technology requirements were to be derived from performance "gaps" of the HMs. These gaps were to be identified from the difference between the HM required performance and the feasible performance of extrapolated current technology. However, it was found that the HM performance requirements described in the literature are based on and thus already carry with them implicit assumptions about the technologies expected to be available. These implicit assumptions were thus found to limit the mission concept, operation and performance-based scenario because they adopt current perceptions of engineering and technological limits. Any derived performance gaps and technology requirements simply took the form of some percentage improvement needed in familiar technologies. Generally, no insights into alternative technology approaches were available. Therefore, a useful methodology required that a higher-order, "technology-independent" parameter be defined.
The parameter that serves this purpose is labeled an engineering assumption. Examination of the implicit assumptions uncovered in the HMs show them to be underlying engineering approaches based on traditional mission operations and functions, which of course are based on conventional systems capabilities and technology extrapolations.

Step 3 of the methodology involves the identification of the implicit engineering assumptions. The full set of implicit assumptions for an HM constitutes a traditional mission design based on conventional technological capabilities. In Step 4 alternative engineering assumptions are generated, from which new system functions and technological capabilities can then be derived. Given alternative system and technological functions, innovative technology ideas and their mission impacts can be examined.

**METHODOLOGY DEMONSTRATION**

Abbreviated analyses of two missions - an Unpiloted Star Probe and a TAU Observatory - are used to illustrate the Horizon Mission methodology. Both HMs are based on a theme that can be postulated for post-Mars space exploration - interstellar and perhaps galactic science. Detailed descriptions of the two and further references are provided in References 1-2. Those descriptions reflect the conventional mission designs based on extrapolation of current technologies and conventional engineering approaches. The results of applying the HM methodology are then presented in terms of alternative engineering assumptions comprised of new functional elements and operational relationships.

**Unpiloted Star Probe (USP)**

Although this mission would be more technologically demanding than the TAU Observatory, it is treated first because of its familiarity. The USP would be targeted for a nearby star system, perhaps the triple star system of Alpha Centauri or Barnard's Star (about 4.3 or 6 light years distant). The USP would:

- Conduct interstellar research ranging from the outer boundaries of our solar system to the edge of our sun's heliosphere, the "pure" interstellar medium of our galaxy and into the heliosphere of another star system,
- Encounter another star with the potential of associated planetary systems and life forms,
- Resolve formidable technology challenges of propulsion, very long life, autonomous operations, scientific instrumentation and data return over 50-100 years and up to 6 light-years.

The conventional engineering approach to the design of a USP is illustrated in the implicit or baseline engineering assumptions summarized in the left column of Figure 3. These reflect the typical engineering approaches for spacecraft system design applied to a star probe mission. Most references for the USP provide similar concepts, characteristics, operational requirements, and hence technology requirements. The Starwisp concept described in Reference 7 is an exception and in fact represents the type of innovative mission concept that could be structured by or come from the HM methodology.

An important characteristic of these implicit assumptions is that they limit the mission concept, operations and performance-based scenario to current perceptions of engineering and technological limits. To circumvent those limits, alternative engineering assumptions must be made. One set of these is shown in the center column of Figure 3. These alternative assumptions are certainly not the only ones possible nor are they necessarily new ideas; most have appeared elsewhere in the literature. In the right column are then shown possible new functional and technological capabilities that could fulfill the requirements of those alternative assumptions.

These needed new capabilities are in part based on the planner's or analyst's knowledge of new technology frontiers, emerging scientific discoveries or analytical advancements. But as is shown below any one of them offers an opportunity to radically alter the specific mission concept, enhance the objectives and illuminate a broader role for that particular innovative technology concept.

The alternative assumptions offer different engineering approaches for mission design, operations or distribution of functions. Three of these assumptions are examined below to illustrate the methodology: microspacecraft, autonomous systems and diamond materials. Because of the obviously speculative nature of some of the following analysis, it is important to restate the intent of this study and report. The purpose of the HM methodology is not to establish real technology options for these missions nor necessarily to conceptually redesign the missions. Its purpose is to provide an engineering framework for evaluating innovative technology concepts, applying them to missions and assessing their potential mission impacts.
The first alternative assumption is the use of microspacecraft with vast information processing capacity and extremely low power requirements instead of the traditional size, mass and monolithic structure of a USP spacecraft. Combinations of supercomputing, computer chip and microelectromechanical device technologies provide the foundation for this alternative. Microspacecraft will constitute new functional elements enabling multiple redundancy (perhaps 10-100 X), shared responsibilities, and distributed functions. Adding nanotechnology (devices, sensors, actuators) to this combination will introduce the functional element of massive redundancy (perhaps 100-1000 X) thereby transforming traditional design concepts of reliability, sensor configurations, and actuator mechanisms.

The second alternative assumption is the use of knowledge systems and autonomous systems instead of information systems and automated systems. Combinations of supercomputing, computational science, chaos theory, nonlinear dynamics, neural networks and various forms of decision-making artificial intelligence provide the foundation for this alternative. For example, applications of chaos theory and non-linear dynamics analysis show promise for extracting regularities from complex time series (e.g., small signals from high noise) and for real-time modeling from sampled data to provide predictive control for future sampling (e.g., real-time autonomous adaptation to unanticipated environmental conditions). Furthermore, a mission designed for knowledge processing and autonomy would yield substantially different engineering and technology considerations than if designed for information processing and automation.

The third alternative assumption is using diamond materials for coatings, substrates and 3-D device configurations instead of traditional materials. Combinations of diamond film, diamond-like film, and fabrication technologies provide the foundation for this alternative. The properties of natural diamond include: greatest known hardness, greatest known thermal conductivity (10X silicon and 5X copper), widest known transparency, chemical inerterness, high temperature stability, low expansion coefficient, excellent electrical insulator, and high radiation damage threshold.

**TAU Observatory (TAO)**

The purpose of addressing the TAU Observatory mission is to examine different technologies related to the same theme – interstellar science. The TAU would be sent to a distance of one thousand astronomical units (TAU) from the Earth, normal to the galactic plane. It is a mission of greater scientific and technological scope than the TAU Probe which has been the subject of several studies (Refs. 8-10). It could be either a successor or an alternative to the TAU Probe, but with much greater requirements on measurement and spacecraft configuration technologies (Refs. 11-12). The Observatory mission would:

- Enable parallax measurements to the edge of the galaxy by increasing the triangular baseline from earth orbit diameter of 2 AU to 1000 AU,
- Observe other star systems using the "gravitational lens" focusing created by the sun. At 1000 AU, as the observatory moves relative to the sun the lens could provide greater than 10^6 power magnification of events in the background as they come into focus (Ref. 11).
Search for: presence of "dark matter", existence of stars closer to the sun than those already known, and a specific companion star to the Sun theorized to have caused cataclysmic earth events on a period of about 30 million years,

- Require the autonomous calibration and operation of an optical telescope and a large scale radio receiver (perhaps a 1 km diameter, Fresnel flat-plate zone receiver).

- Resolve technological challenges of: self-assembly of a large-scale structure and long-term autonomous configuration management and fine surface control of a multispectral receiver; small independent station-keeping, scanning receiver(s) moving along the optical axis; observatory pointing and signal correlation for a 1000 AU baseline interferometer.

The Einstein Cross (Figure 5) is a dramatic example of the gravitational lens effect. The image was taken by the European Space Agency's Faint Object Camera, an instrument onboard NASA's Hubble Space Telescope. The figure shows a quadrupole image of a distant quasar (about 8 billion light-years) brought to focus at the earth by the gravitational field of Galaxy 3C273 + 0305 (about 440 million light-years distant). Gravitational lens effects of our sun begin at about 550 AU (Ref. 11).

The engineering assumptions and new functional and technological capabilities for the TAO mission are shown in Figure 4. The TAU Probe descriptions provide the basic mission upon which to define the more ambitious TAU Observatory. The TAO mission scenario is as follows. The spacecraft would be configured at the outset for the chemical or nuclear thermal propulsion burn to obtain an interstellar trajectory and then for perhaps a 10 year nuclear electric propulsion phase (of much smaller thrust). Once the g-loaded phases are completed, then the assembly of the observing/receiving and transmitting structure could begin. In the conventional engineering concepts for the TAU Probe, the reconfigurable components of the spacecraft are few and monolithic and thus readily deployed or extended into place. For the TAU Observatory the radio receiver would be a large-scale structure, perhaps a "gossamer-like" Fresnel flat-plate zone lens similar to those described in References 7 or 12.

Two alternative engineering assumptions for this HM are examined below: aero-gravity trajectory assist to greatly reduce trip time and autonomous assembly and configuration management of large scale space structures.

Solar system spacecraft occasionally use Jupiter Gravity Assist (JGA) to acquire added Δv for a mission. In fact, a trip time reduction of 10 years (from 50 to 40 years) for the TAU Probe could be obtained by using JGA (Ref. 8). Hypersonic waverider technology offers the further possibility of using the atmospheres of terrestrial planets to gain significant additional Δv. Hypersonic waverider describes an aerospace vehicle configuration that permits the hypersonic shock wave to remain attached to the vehicle surface. This condition permits the lift-over-drag ratio of the vehicle to be considerably higher (and thus energy loss lower) than for traditional hypersonic vehicle designs. Use of a waverider shell (inverted for negative lift) for a spacecraft destined for the outer solar system or beyond would permit Aero-Gravity Assists (AGA) in the Venus, Earth and/or Mars atmospheres (Ref. 13-14). Mission trajectory calculations of Reference 14 provide the following comparisons. Terrestrial planet AGA could provide flight times of less than 5 years to Pluto compared to about 15 years using JGA alone. Further reductions could be obtained in the TAO mission flight time based on the following Δv comparisons (Ref. 14): JGA provides a Δv of about 15 km/s, Venus AGA about 15 km/s, and Mars AGA almost 30 km/s. In addition to much greater escape velocity these Δv gains from hypersonic waverider technology could allow greater orbit or trajectory inclination and apsidal rotation.

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<th>BASELINE - IMPLICIT *</th>
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<th>NEW FUNCTIONS &amp; TECH CAPABILITIES</th>
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<td>MONOLITHIC, ROID STRUCTURES: OPTICAL &amp; IR TELESCOPE BPM STABILIZED</td>
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* BASED ON MISSION DESCRIPTIONS FOR TAU PROBE

Figure 4. TAU Observatory - Engineering Assumptions
Figure 5. The Einstein Cross

The autonomous assembly of a large Fresnel flat-plate zone receiver to act as a spectrometer might be carried out by a small robot retrieving, transporting and affixing modular units to build up a large mosaic structure, by self-deployment of nested congruent modules (e.g., “telescoping”), or through use of a thin mylar film, alternately aluminized and clear in annular Fresnel zones and stretched across a 1 km circular hoop. The startup and long-term operation of the Observatory would involve adaptive reconfiguration of the structure to provide instrument calibration, system pointing and control, multispectral fine pointing and control, receiver/transmitter reconfiguring, and stationkeeping and traversal of a scanning receiver along the optical axis. The foundation for this capability may be found in today’s smart materials and structures, shape memory metals, adaptive optics, photonics, nanotechnology sensors and actuators, and artificial intelligence.

USES OF HM METHODOLOGY

Even this abbreviated exercise in the use of HMs provides some beginning insights into potential mission impacts of current technological frontiers. However, these observations could have been obtained without the Horizon Missions. So what’s new? Three things are.

1. Typically, the anticipation and prediction of future technology uses is done through creative free association by scientists and engineers. The HM methodology provides a specific engineering framework of a hypothetical mission into which innovative technology ideas can be inserted. By linking the creative process of generating technology concepts to a framework of HM requirements, an internal system consistency is obtained and the process can be systematically repeated and results compared.

2. The HM methodology helps suspend the strong natural and pragmatic tendency to plan based on familiar engineering systems and functions. The different, perhaps unfamiliar engineering framework or paradigm that is fashioned from the HMs enables innovative technology ideas to be considered for performing new functions that are not possible within conventional frameworks.

3. Any Horizon Mission provides a “requirement” for new capabilities that can only be enabled by highly innovative new technologies. This is analogous to the Apollo Mission requiring fundamentally new, not just improved, capabilities in electronics and entry technologies. Without Apollo, those technologies would have remained merely latent ideas - until some other impetus for their development into specific, demonstrable concepts came along. The HM “requirements” provide such an impetus, by permitting breakthrough-type technology ideas to receive much earlier-than-normal conceptual development directed toward specific mission functions. This could accelerate the availability of revolutionary new space capabilities.

The HM methodology along with its supporting data base provides an analytical tool which can be used in at least three areas of space studies.

First, for Advanced Technology Planning it can provide a systematic means of evaluation and even strategic prioritization for new areas of highly innovative space technology research. High payoff, high risk “breakthrough-type” technology concepts are difficult to compare on any common basis. Even when “proof of concept” has been established, the unfamiliarity of the technology usually prevents evaluation by the conventional standards for validated technologies. HMs permit a spectrum of possible applications to be identified for any single technology through its incorporation into different functional elements and operational relationships. Engineering systems incorporating the breakthrough technology can then be defined to meet mission requirements. Figure 6 is a graphical depiction of this particular use of the methodology.

The HM methodology provides a specific analytical tool for conducting advanced concept studies of broader-than-normal scope. Typically, advanced
concept studies extrapolate the properties of known, emerging space technologies to enable a specific advanced mission. In these studies a large measure of conventional engineering practicality is required because support is being sought for further mission definition or technology research. Therefore, the more highly innovative, less proven, or more speculative technology ideas are usually not included. On the occasions when they are, only a single use of the technology is typically examined. But as studies of breakthroughs have shown, their greatest impacts are often not on the functions they were initially designed to fulfill but instead on new functions and operational relationships that were unforeseen. Therefore, technology analysis and planning from advanced concept studies that are based on narrow usage of a breakthrough idea can be severely limited. The HM methodology can be used to explore an expanded range of space functions and operational relationships that could be enabled by breakthrough-class space technologies, new non-space technology frontiers, and even speculative technologies based on new scientific discoveries.

Figure 6. Evaluation of Breakthrough Technology Concepts Using Horizon Missions

Figure 7. Products Available From the Horizon Mission Methodology

<table>
<thead>
<tr>
<th>FUNCTIONAL USES</th>
<th>PRODUCTS PROVIDED</th>
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<tbody>
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<td>ADVANCED TECHNOLOGY PLANNING</td>
<td>Prioritization of Breakthrough Ideas</td>
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<td>Far-End Strategic Planning</td>
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<td>Exploratory Requirements Analysis</td>
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<tr>
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Second, for Advanced Mission Planning the methodology can be used to generate alternative mission concepts made possible by a breakthrough technology. Once the functional elements and operational relationships are specified for a mission then alternative mission designs and scenarios may be created. Mission alternatives may yield different strategic guidance for advanced technology research.

Third, for University Studies the methodology can provide a framework and tool for conducting multidisciplinary studies and analyses of advanced missions, space systems, and their technology requirements. Thus for workshops, summer faculty studies, cross-disciplinary university classes, and exploratory design studies, the methodology and database provide an integrating framework.

One final point - in the preceding HM exercises the lists of alternative engineering assumptions tend to be technology-stimulated and depend on the analyst's or designer's knowledge or creativity. Thus, the lists do not reflect any overall theme or unifying thread. However, unifying themes could be developed in the form of alternative engineering paradigms. For example, an entire mission or spacecraft could be designed using all foreseeable applications of nanotechnology, diamond films or high temperature superconductivity. However, it is beyond the scope of this study to examine the topic of alternative engineering paradigms.

CONCLUDING REMARKS

Breakthroughs in space technology will occur and will provide revolutionary improvements in capabilities for space missions of the 21st century. It thus provides an analytical tool that permits the performance jump or radical new capability of a breakthrough technology concept to be accounted for in the planning and analysis for advanced space missions and advanced technology research. The use of this HM methodology does require a mental discipline to "stay in character" and not revert to conventional evaluations of mission or technology feasibility. Remember that the methodology is intended to provide understanding of applicability and performance, not to establish feasibility.

REFERENCES