Microwave Systems Applications in Deep Space Telecommunications and Navigation: Space Exploration Initiative Architectures

Justin R. Hall, Rolf C. Hastrup, and David J. Bell

Abstract—**The United States Space Exploration Initiative (SEI) calls for the charting of a new and evolving manned course to the Moon, Mars, and beyond. The fundamental SEI support objectives are to provide the mission with means to monitor and control mission elements, acquire engineering, science, and navigation data, compute state vectors and navigate, and move these data efficiently and automatically between mission nodes for timely analysis and decision-making. Microwave links provide the means to communicate between system nodes, and the essential radio metrics to navigate; later, these likely will be augmented with optical links. Although these objectives do not depart, fundamentally, from those evolved over the past 30 years in supporting deep space robotic exploration, there are several new challenges. This paper first familiarizes the reader with the general mission telecommunications and navigation support requirements and resulting architectures for SEI mission support, and then discusses the implications of these on the role of microwave technology in these architectures, particularly for Mars exploration support. Effective use of microwave technology is enabling, and obviously the sine qua non of the mission support architecture.**

I. Introduction

The Space Exploration Initiative (SEI), also known as "Mission From Planet Earth," calls for the charting of a new and continuing manned course to the Moon, Mars, and beyond. This initiative poses a number of interesting architectural and technology challenges for Mars deep space telecommunications, navigation, and information management (TNIM) support functions. The fundamental objectives are to provide the mission with effective means to monitor and control mission elements, acquire engineering, science, and radio metric navigation data, compute state vectors and navigate, and move all of the associated data efficiently and automatically between mission nodes for timely analysis and decision making. These objectives do not depart fundamentally from our objectives and experience over the past 30 years in supporting deep space robotic exploration; there are, however, several significant differences.

In general, lunar SEI requirements on the TNIM architecture and technology are far less demanding than those for Mars; however, viable lunar mission testbeds will be critical in developing and validating the enabling technology pivotal to successful Mars exploration and operations [1].

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In the following sections, the general support requirements of a typical SEI mission set, the mission operations objectives, and related TNIM support infrastructure options are described. Then, responsive system architectures and designs are proposed, including a Mars orbiting communications relay satellite system, and a Mars-centered navigation capability for servicing all Mars missions. With the TNIM architecture as a basis, key elements of the microwave link design are proposed. Finally, the needed new technologies, which enable these designs, are identified and current maturity is assessed.

II. Requirements

A typical SEI mission set, shown in Fig. 1, has been used as a reference for conducting SEI studies [2]; it embodies most of the mission challenges expected, and represents a long-term evolutionary program. Robotic missions are required as precursors to the piloted missions to provide important science and engineering data for the Moon and Mars, to demonstrate enabling technology, and evolve operations concepts. The robotic exploration missions include globally distributed, surface-fixed instruments, surface rovers, and imaging orbiters. The next step in the evolutionary process is to establish a permanent human outpost on the Moon for science, exploration, potential resource utilization, and testbed operations in preparation for Mars missions. After lunar experience is gained, including demonstration of needed concepts and techniques, the first piloted missions to Mars will be conducted. Later missions will establish an outpost on Mars, from which extensive exploration can be conducted, including the use of manned rovers. Fig. 1 also depicts a relative schedule for evolving telecom/navigation relay capability for support of these missions.

Mission Operations Concepts Driving TNIM Requirements

The effects of round-trip light-time delay (latency) and link line-of-sight occultations have a major impact on real-time mission operations decision-making; both local Mars

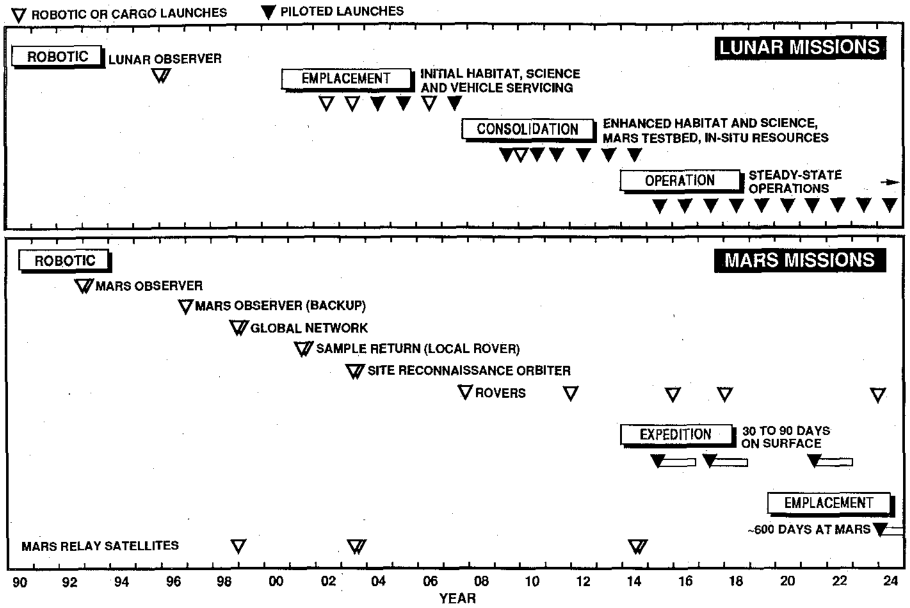

Fig. 1. Space Exploration Initiative mission set (typical reference missions).

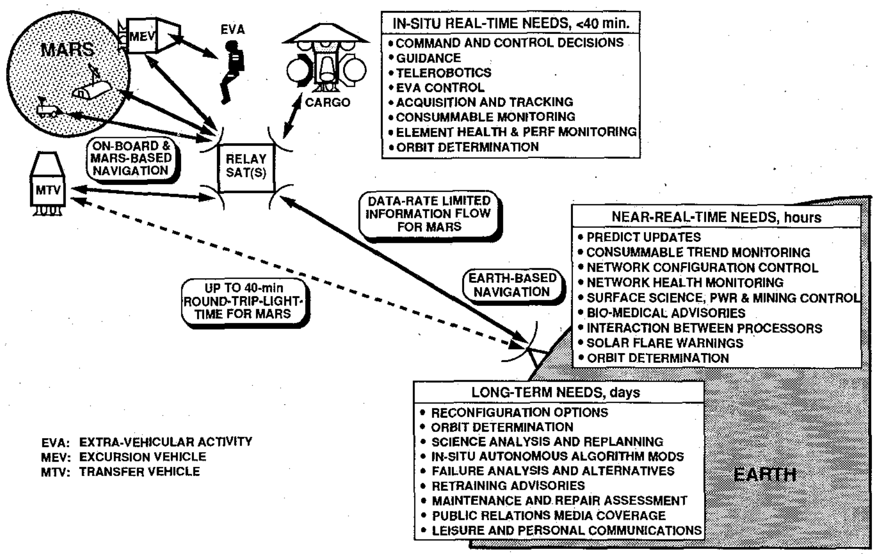

Fig. 2. Deep space mission data functions (typical examples for Mars).

and Earth-based functional control centers are needed. It is not at all surprising that many critical Mars *in situ* control decisions, reacting to continuing, rapidly-sequencing events, cannot await the time delay in transit (up to 40 minutes round trip) and remote processing at central mission control centers; further, these critical decisions are hostage to time-latent input data. Fig. 2 illustrates examples of typical functions that will be performed *in situ* and on Earth, and which require mission data that must be interchanged between nodes. This decentralized control approach is driven both by time latency and system complexity, and is key to mission robustness (functional redundancy) and, indeed, success.

Telecommunications Requirements

The data types requiring transmission between Mars and Earth include high and low rate video, voice, science and engineering telemetry, and commands. Transmission of these data types plus telerobotics data is also required between *in situ* terminals at Mars. The key data rate driver is 10 Mb/s compressed real-time video between Mars and Earth (both up- and down-link video are required) [1]. This link performance is needed for the Mars transport vehicle and for Mars surface terminals. The maximum data rate of 50 Mb/s between in-situ elements is driven by telerobotics needs (simultaneous operation of two robotic mechanisms). Link connectivity between manned terminals and to Earth is required at least 95 percent of the time. Support of up to 5 concurrent up and down links with Earth is required to cover the later phases of exploration activities at Mars and the Moon. Emergency telecom links are mandatory.

Navigation Requirements

Manned and unmanned spacecraft must be navigated during all phases of the SEI missions, including transit to and from the Moon and Mars, propulsive or aerobraking insertion into orbit, on orbit, landing and ascent to and from the surface, and rendezvous. Surface rovers must be navigated with respect to other surface elements, hazards, and features to be explored.

The most challenging mission navigation requirements are to provide the Mars approaching spacecraft with the trajectory accuracy needed if aerobraking is used for capture into Mars orbit, and to provide precision landing on Mars' surface. Based on preliminary analyses [3], the driving navigation requirement ($3\ \sigma$) for aerocapture may reasonably be expected to be on the order of 5 to 20 km uncertainty in altitude and 10 to 40 km uncertainty in position along the flight path at atmospheric entry, depending on the values assumed for lift/drag, g-load limit, atmospheric density uncertainty, and available propulsive capability for orbit circularization after capture. Propulsive capture using chemical or nuclear-thermal engines is less demanding on the navigation system. The final landing accuracy requirement is expected to be on the order of 10 m.

III. The Architecture and System Design

Distillation of the above requirements leads to several system design challenges which affect the microwave design. These are: 1) telecommunications and radio metric functions within a large distributed system, incorporating relay satellites to achieve high connectivity for both manned and robotic links, 2) highly unattended operations for *in situ* Mars telecommunications and navigation functions, 3) real-time video data rates, and 4) accurate radio metrics.

The related microwave and data challenges include: 1) efficient and reliable microwave elements above *X* band, 2) automatic in-situ link acquisition and tracking, 3) Earth-based antenna gain appropriate to reasonable antenna foot print size at planetary ranges, 4) reliable and efficient spacecraft/lander microwave transmit power generation, 5) efficient and robust unified telecommunications and radio-metric microwave systems, and 6) effective image compression methodologies for achieving high video throughput. Spacecraft docking and landing will use both optical and microwave measurement devices, and are covered briefly in the conclusions.

To begin, there are some significant differences in design for providing the TNIM support functions at the Moon and at Mars. Mars is one-thousand times more distant than the Moon. Available RF bandwidth is the major lunar-Earth link data-rate design constraint; signal-to-noise-ratio is a key Mars-Earth link constraint. For Mars, up to 40 minutes away in two-way light time, mission monitor and control approaches are significantly different; limited staffing will require wide use of unattended TNIM operations functions, and a high degree of local navigation autonomy at Mars. These considerations may lead to Mars spacecraft TNIM systems designs that require different optimizations from those developed for lunar applications; for example, the lunar telecom relay is mandatory to communicate to far-side nodes but not critically useful for near-side nodes, and, most likely, will be of the "halo orbit" type (quasi-stable orbit behind the Moon about the farside libration point, L2).

Configuration Concepts

Fig. 3 illustrates the key elements of the baseline lunar and Mars TNIM networks, and depicts the overall configuration and high-level functions, interfaces, and flow. Low Earth orbit (LEO) service is expected to be provided by the space-based Advanced Tracking and Data Relay Satellite System (ATDRSS). This service supports data transfer connectivity for Earth launches, reentry, and SEI Earth orbital operations. Outside of low-Earth orbit, service will be provided by an expanded Earth-based Deep Space Network (DSN), and by *in-situ* relay orbiters. TNIM network interfaces with mission elements for lunar/Mars exploration will exist at four different locations: 1) in Earth orbit, 2) at transport vehicles in transit and in lunar/Mars orbit either directly to the DSN or via telecom relay, 3) at Mars and lunar surface nodes, and 4) on Earth between the DSN/ATDRSS and the mission operations center.

Telecom Concepts

Frequency selection trades in antenna directivity and weather effects are pivotal. Higher microwave frequencies used between constant area directional antennas result in more received power because of the smaller beamwidth of the transmitting antenna; this is proportional to the square of the frequency. However, there are mitigating effects: 1) antenna pointing is more difficult; needed pointing accuracy is linear in frequency, and wind effects are critical for large ground antennas, 2) required antenna surface accuracy is linear in frequency (e.g., at 32 GHz, surface smoothness to 0.5 mm is required), 3) weather effects on system temperature and attenuation are more pronounced at higher microwave frequencies, 4) planets in the receive beam become critical noise sources in low noise (20 K system temperature) high gain antennas (e.g., for Venus at 2 GHz, 11 K is added; at 32 GHz, 600 K is added). Thus, all other effects tend to reduce theoretical data rate as frequencies increase beyond 32 GHz; never-

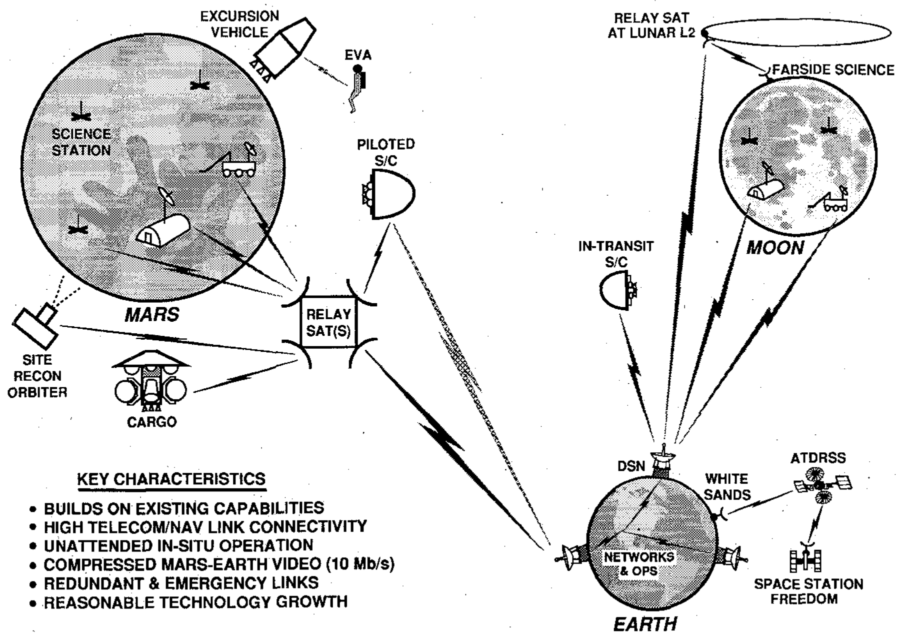

Fig. 3. TNIM system architecture.

theless, careful engineering and weather strategy make 32 GHz for deep space telemetry a good investment. For example, *Ka*-band should provide a factor of four to six in SNR improvement over the current *X*-band capability, considering weather, system temperature, and antenna surface accuracies [4]; also, 30–40 GHz is the only reasonably low atmospheric absorption window above 20 GHz.

The high data rate needs focus on both use of higher frequencies (*Ka*-band at 32 GHz for Mars) and effective data compression algorithms. Both of these capabilities are technology drivers. *Ka*-band systems are planned for demonstration during the lunar phase, and during the robotics program at Mars. Data rates to Earth, much in excess of 10 Mb/s, may require use of parallel microwave links or, during later phases beginning after about 2020, optical communications links. Deep space optical telemetry links would require demonstration prior to operational use. Practical optical link designs may provide data rate increases of over one hundred times the *Ka*-band link performance, but much development work remains [5], [6]. Use of optical, in addition to microwave frequencies, would enhance both local Mars and Mars-Earth links, and should be phased into the development sequence of the SEI when sufficient optical technology maturity is achieved. If optical links are introduced to enhance telecommunications data throughput capability, the navigation implications of optical-metric data will require consideration, since these telecommunications links will be photon (energy) links rather than phase coherent links. Table I compares a number of key trade parameters in the selection of *X*-band, *Ka*-band, and optical frequencies.

Unattended operation is particularly important for *in situ* telecom and radio-metric data acquisition and tracking. The high performance links needed require high gain, narrow beamwidth antennas on both ends of the link. Lower gain antennas, used almost universally in the Apollo mission, will mainly be employed for link acquisition, low rate *in situ*, or fail-soft applications. High gain antennas for Mars-Earth links must be able to be pointed to within 0.05 degrees of Earth at all times; in-situ links between spacecraft or lander terminals with 0.2 degree antenna beamwidths may be at 70 000 km range or within a few tens of kilometers, or closer, and must accommodate high Doppler and angular rates. Further, link interruptions from occultation events must be predicted. These, and predicts for frequency data, which include *a priori* rest frequencies, relative Doppler and rate parameters, require that state vectors and computing capability be available in each vehicle for generation of these predictions for all required links. Link acquisition requires searching in space, frequency, and time, all of this normally orchestrated by a local sequence-of-events schedule provided, and periodically updated, via mission control.

In-situ Mars and lunar links, and Earth-lunar links most likely will use the 37- to 40-GHz allocation now being recommended to the ITU [7]. Joint use of the same *Ka*-band frequencies for both lunar- and Mars-Earth links is not recommended because of the local interference potential at the DSN receiver location resulting from the nominal 60-dB difference in path loss to Earth. Further, DSN cross-support advantages for Mars and other deep space missions will, most likely, dictate use of *Ka*-band 32–34 GHz for all deep space applications.

Earth Networks

The ground network SEI supporting functions are logical extensions of the current DSN architecture [8]. Three

TABLE I
COMPARISON OF FREQUENCIES FOR MARS-EARTH LINKS

	X-Band 8.4 GHz	— ×4 →	Ka-Band 32.4 GHz	— ×17500 →	Optical Band 0.5 μ
Data Rate, Mb/s	1		10***		100***
Transmit Power, W	100		70		10
Transmit Antenna Diameter, m	5		5		0.5
Receive Antenna Diameter, m	70 (or 4 × 34)		70 (or 4 × 34)		10 (Photon Telescope)
Earth Footprint (1/2 power), km*	1.1×10^6		2.8×10^5		150
Mars Footprint (1/2 power), km*	7.7×10^4		2 to 7** $\times 10^4$		~800
Mars Activity Diam, km	7×10^4		7×10^4		7×10^4

*For antenna receiving from 1 au.
**Using 34-m array beam forming.
***Clear, dry weather.

complexes, located at approximately 120 degree intervals in Earth longitude, provide continuous view of all deep space vehicles within ±30 degrees declination; these are connected to a central network monitor and control facility through the use of cable and satellite links. The DSN interfaces directly with mission operations monitor and control elements (reference Fig. 3). A 34-m antenna, operating with X-band uplink frequencies at 7 GHz and maximum power of 20 kw, provides at least a 10-Mb/s capability to Mars for video and data transmission for normal spacecraft support. The 70-m subnet will continue to provide high power uplinks (100 to 450 kW, CW) for emergency deep space commands at both S- and X-bands, and for planetary radar applications.

The DSN antenna "footprint" (see Table I) at Mars range becomes a critical parameter. The diameter of the activity area at Mars, as seen from the Earth, is about 70 000 km to cover the surface and orbiters. A 70-m diameter antenna aperture, receiving at 32 GHz, is required to satisfy the minimum data rate needs at maximum range. This assumes a 5-m antenna and 70-W RF transmitter power on the spacecraft. The 70-m antenna footprint varies from about 10 000 km to about 40 000 km at maximum range. Clearly, there is a coverage design issue, since a number of distributed direct and relay links are involved, and the local activity diameter at Mars can change hourly. The architectural concept being proposed is an array of at least four 34-m antennas which have the following key characteristics: 1) if maximum data rate is needed at any particular point at Mars, all can be optimally arrayed, equivalent to a 70-m antenna; 2) the pointing of each antenna can be skewed in a continuously programmed manner to create the necessary pattern of the array to fit the geometry of Mars telecom activity and data rate needs; 3) the array provides a fail-soft option in the event of individual antenna failures; and 4) individual antennas may be used to support lunar SEI and other missions as the range to Mars decreases (data rate capability varies inversely as range squared, but the compensating footprint diameter decreases linearly as range). Figure 4 in [9] depicts typical Mars-Earth data rate capability versus range over the synodic period.

Mars Telecom/Navigation Relay Networks

A relay satellite network provides several advantages for both robotic and manned SEI missions [10]. Very significant improvements can be achieved in link connectivity and performance for both the links between Mars and Earth, and the local Mars links. Relays are necessary to meet the 95 percent connectivity requirement for manned nodes. The connectivity and performance improvement provided by the relay network also permits use of simpler, lower performance, and less costly telecom subsystems for the *in situ* mission exploration elements. As will be explained later, orbiting relay satellites can also serve as effective navigation aids by providing Mars-centered radio-metric data which includes Mars ephemerides uncertainties. The relay network also provides redundant and backup communications links as well as emergency links; it provides a factor of a thousand times increased emergency link data rate performance as compared to space craft omni-antenna links directly to Earth, as well as greatly increased connectivity.

It is expected that required communications coverage of a variety of SEI robotic and manned in-situ vehicles and surface stations will need an evolving relay support infrastructure which may include: 1) low altitude, perhaps lower performance relays in highly inclined orbits for initial, globally distributed small robotic surface science packages, and 2) large, higher performance, circular Mars-synchronous orbits and/or "molniya" (elliptical, non-precessing) orbits for imaging orbiter, manned vehicle and surface habitat coverage. These relay orbiters will evolve from simple, low-rate, "bent-pipe" configurations for early missions, to high-rate multiple link vehicles, with message switching, to support later manned missions. Most likely, a constellation of satellites in both highly inclined and equatorial orbits will constitute the final coverage configuration to support, in the long term, a variety of *in situ* terminals. Finally, it is important that the requirements on and operations of a relay network not insert a third party in series with what is currently a very complex tracking and communications interface between the mission and data acquisition network.

TABLE II
TNIM TECHNOLOGY REQUIREMENTS AND MATURITY

TNIM Technology Item	Technology Requirement	Maturity Level*
Telecommunications		
Ka-band TWTA transmitters	10–150 W high-efficiency	4
Ka-band solid-state transmitters	1–15 W high-efficiency	2–3
Multibeam antennas (electronically steered)	10–20 simultaneous beams	5
MMIC** multibeam antennas (electronically steered)	10–20 simultaneous beams	2
Direct-radiating MMIC** phased array	10 × 10 array	3
Reconfigurable antennas	Operation at *Ka*-band	2
MMIC technology	Higher power, lower noise	3–4
Optical technology	Higher power laser source	2
Navigation		
Sensors	IMU***, altimeter, press, temp	3
Computers	Autonomous navigation capability	3
Information Management		
Data compression	10 : 1 compression (acceptable for science applications)	6
Data storage	10^{12} byte storage capacity	2
Autonomous network control	Unattended operations/fault tolerant designs	2

*Technology maturity levels are defined as follows:
Level 1: Basic principals observed & reported
Level 2: Technology concept/application formulated
Level 3: Analytical & experimental critical function and/or characteristic proof-of-concept
Level 4: Component and/or breadboard validated in laboratory
Level 5: Component and/or breadboard demonstrated in relevant environment
Level 6: System validation model demonstrated in relevant/simulated environment
Level 7: System validation model demonstrated in space
**Monolithic microwave integrated circuit.
***Inertial measurement unit.

Radio-Metric Concepts for Navigation

A variety of data types for navigation are envisioned, including Earth-based Doppler, ranging and very long baseline interferometry (VLBI), on-board optical tracking of Mars, Phobos and Deimos, *in-situ* ranging and Doppler using orbiting spacecraft (e.g., the relay satellites) and surface beacons [11], [12]. Dual frequency, 8- and 32-GHz, links provide for accurate charged particle calibration (and radio science measurements) at Earth. Earth-based frequency standards provide system frequency stabilities over the two-way light time of better than a few parts in 10E14.

VLBI is effective for measuring the direction (to 5 nanoradians) to a spacecraft, or distance between two distant communications spacecraft very accurately (to 10 picoradians) [12]. Signals from an *in situ* spacecraft or lander are received concurrently by the two widely-spaced Earth tracking stations, which provide the very long baseline. Interferometric measurement of phase or arrival time delay determines the direction to the two tracking stations. With a third tracking station not in the same plane, the direction to the spacecraft can be determined completely. The technique can also use signals radiated by two or more spacecraft to determine the angle between them to even better accuracy because many systematic errors cancel, particularly between two spacecraft when both are within the same beamwidth. This leads to an interesting VLBI frequency selection trade off for tracking an approaching spacecraft relative to a beacon at Mars; higher frequencies provide more accurate angles at the picoradian level, but narrower beam widths limit dual spacecraft/beacon time-in-beam measurements, hence less time and more impulse to correct navigation errors!

Operations Concepts

Most of today's manned mission, TNIM-related operations are highly manpower intensive. *In-situ* Mars mission operations, if forced to operate using attended monitor and control techniques, could be nearly intractable, or at least unaffordable, because of the complexity and astronaut staff needs. The resulting pay-off for unattended TNIM operations is that astronauts can be far more effective in accomplishing direct, mission-related tasks. Indeed, the availability of increased *in situ* monitor and control automata, including increased processing capability and mass data storage at remote Mars operations centers, are pivotal and mission enabling. Not only must local decision-making be assisted through experience-based inference machines, but, also, the links to distribute this information rapidly to other system nodes must operate largely unattended [1].

IV. TECHNOLOGY AND OPTIONS

New technology needs, maturity assessment, and alternatives for mission support are summarized in Table II.

They are, in general, enabling for high rate telecommunications, unattended operations, and time latent distributed operations. Perhaps, the next most important phase after achieving technology maturity is validation of these technologies as integral functions in advanced engineering system demonstrations. For example, one of the principal objectives for early phase, manned lunar operations will be the testing of unattended operations designs, prior to Mars system implementation. Finally, while not included in the TNIM enabling technologies, it will be imperative for the mission to develop expert *in situ* systems capability, in small boxes that must complement the many tens of decision-making experts now located at manned mission control facilities on Earth. This capability will fill in the 40-minute time-latent void in Earth-based mission operations support for Mars deep space manned exploration.

V. Conclusions, and the Future

Microwaves for space communications and navigation radio metrics will meet the assumed or negotiated SEI requirements for data rates and navigation accuracies, but many challenges exist in bringing *Ka*-band components into operational use. Bit rate requirements beyond 50 Mb/s will most likely use optical links, but this is not expected to be needed prior to about the year 2020; however, the SEI program could be a valuable test bed for these higher rate optical systems, which could be used to enhance ongoing missions during the demonstration period. Optical metrics are currently available for close range docking and the like, but phase sensitive optical techniques for long range navigation applications are still well within their conceptual phase. A critical optical system milestone will be a demonstration of the feasibility of Earth-based telescopes in weather diverse locations, versus higher-cost Earth orbital telescope terminals.

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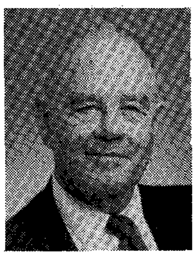

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