NASA Technical Memorandum 105308
AIAA-91-3424

IN-91
58233
P-11

Overview of Ka-Band Communications Technology Requirements for the Space Exploration Initiative

(NASA-TM-105308) OVERVIEW OF Ka-BAND COMMUNICATIONS TECHNOLOGY REQUIREMENTS FOR THE SPACE EXPLORATION INITIATIVE (NASA) 11 p CSCL 03B

N92-14953

Unclas
G3/91 0058233

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Prepared for the
Conference on Advanced Space Exploration Initiative Technologies
cosponsored by AIAA, NASA, and OAI
Cleveland, Ohio, September 4–6, 1991

OVERVIEW OF KA-BAND COMMUNICATIONS TECHNOLOGY REQUIREMENTS FOR THE SPACE EXPLORATION INITIATIVE

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Abstract

In the Space Exploration Initiative Ka-band frequencies are likely to carry the bulk of the communications traffic both in the vicinity of and on the return links from the moon and Mars. This paper examines the four exploration architectures identified by the Synthesis Group and identifies Ka-band technology requirements to meet the data traffic needs and schedule. Specific Ka-band technology requirements identified are: transmitters - 0.5 to 200 W with high efficiency; antennas - 5m and 9m diameter, with multiple beams and/or scanning beams; and spacecraft receivers - noise figure of 2 dB. For each component, the current state of technology is assessed and needed technology development programs are identified. It is concluded that to meet the schedules of lunar and Mars precursor missions beginning in approximately the year 2000, aggressive technology development and advanced development programs are required immediately for Ka-band communications systems components. Additionally, the greater data transmission rates for the cargo and piloted phases of the exploration program require further Ka-band communications technology developments targeted for operations beginning in about 2010.

1.0 Introduction

The Space Exploration Initiative (SEI) proposes a program of lunar and planetary exploration beginning with precursor science and data gathering missions in the late 1990's and continuing through to manned trips to Mars beginning at about 2014. In order to ensure success of these missions and to maximize the value to the United States and to the world, effective, reliable communications are needed from Earth (for command and control), among mission elements (for coordination), and back to Earth (for status reports, data transmissions, and reporting results). The scenarios proposed are complex and include science instruments, robotic and manned rovers, habitats, transfer vehicles, orbiting vehicles, and relay satellites. (See figure 1). To effect these communications links requires the establishment of a communications infrastructure not unlike that which we have on Earth. The exploration program will require point-to-point surface communications on the moon and Mars; mobile communications with rovers and robotic and piloted spacecraft; message switching and routing centers; and relay satellites for nearly full spherical coverage, just to name a few of the infrastructure elements.

A wide range of frequencies will be used for SEI communications. UHF (Near 300 MHz) might be used for line of sight, surface communications. X-band (8 GHz) will be used for communications from Earth. Ka-band (between 30 and 40 GHz) will likely be used for long-distance interconnects at the moon and Mars, and for transmissions back to Earth. Millimeter wave communications up to 300 GHz may find some application where high gain, small size antennas are needed. Future SEI communications data rate growth may require optical communications. In this paper, it is assumed that Ka-band will be the frequency of choice for the bulk of the communications on the major links of the SEI system. (The selection of frequencies for the various communications links is still under study, and the tradeoffs to be made are quite complex. See Refs. 1, 2, 3, and 4. Without engaging in those comparisons, this paper indicates what Ka-band systems might be needed and what technology requirements result.)

The report of the Synthesis Group for SEI (Ref. 5) outlines some alternative architectures and schedules for America's future space exploration. Table 1 lists missions and timetables for the four architectures. At this point in time, one cannot be sure which architecture(s) will be selected. But scanning Table 1 and combining that information with frequency studies underway, it is concluded that likely Ka-band communications applied to SEI needs will be as shown in Table 2. Precursors to the moon and Mars will span the period 1998-2007. Table 2 shows the more complex cargo and piloted missions for both the moon and Mars as separated into initial operational phases and later operational phases with likely increased communications demands. Table 2 summarizes the mission timetable for Ka-band communications developments for the SEI program.

The next section of this paper identifies Ka-band communications system concepts that meet the mission and schedule requirements of Table 2. Then technical requirements are developed for the communications system components, including transmitters, antennas, receivers, and on-board processors. Assessments are made of technology readiness relative to the mission schedules, and, where needed, technology development and advanced development programs are identified for Ka-band communications technologies.

2.0 Technical Requirements of Ka-Band Communications

Discussions designs of major communications links required for the exploration program are given in the next two sections. Emphasis is given to the highest power, longest paths, i.e., the return links to Earth. The link designs establish the technology requirements for the Ka-band communications systems.

2.1 Lunar Exploration Communications

The proposed activities in the lunar portion of the SEI program include science instruments, robotic and manned rovers, habitats, orbiting vehicles, and landers. Ka-band communications links back to Earth provide the required data interconnects, as shown in Figure 2. Activity is concentrated on the front side of the moon, so direct links back to Earth are available.

Where elements are within range of the Lunar Surface Transmitter (LST), networks are established on the moon for interconnections and the return link via the LST. Reception of signals at the Earth is by 34m antennas at the three sites of the Deep Space Network (DSN).

Key communications return link requirements from the moon are given in Table 3. Transmitter powers range from 4 to 100 W, with the lower levels achievable with solid state power amplifiers (SSPA's) and the higher powers requiring travelling wave tube amplifiers (TWTA's). Transmit antennas required are single beam and of moderate size (2m diameter for the largest).

Links required to establish communications networks on and in the vicinity of the moon, are at lower power levels than the return links to Earth. Thus, the Ka-band transmitter technology developed for the return links will suffice for the lunar networks. An additional technical requirement may be for steerable multibeam antennas, or scanning beam antennas, to be used on the lunar orbiter functioning in a relay satellite mode as part of the lunar network concept.

The data rates shown in Table 3 for the lunar return links during the cargo and piloted missions, are high enough to accommodate simultaneously, several full motion video channels and high data rate scientific instruments. But for high definition television images, compression ratios of at least 2:1 or 4:1 will be required to allow transmission of images at the Ka-band transmitter power levels and antenna sizes shown. Additionally, part of the purpose of the lunar phase of the SEI program is to test and operate the actual equipment and systems to be used for the Mars missions. In those cases, higher video data compression ratios will be achieved and the Ka-band technology needs shown in Table 3 will accommodate a very large number of video and science data channels.

2.2 Mars Exploration Communications

Exploration of Mars is planned to include a series of precursor missions to obtain additional scientific, geological, and topographic data to aid in exploration planning. The cargo and piloted phases of the mission will follow and will include science instrument networks, robotic and manned rovers, habitats, orbiting vehicles, communications relay satellites, and landers. The communications concept for Mars exploration is as shown in Figure 3. Activity is expected over most of the sphere of Mars. Mars Relay Satellites (MRS's) will provide the system networking and the primary high data rate, Ka-band, return links to the Earth. Direct communications back to Earth will also be available from the habitat and from Mars transfer vehicles (MTV's) while en route. Signals will be received at the Earth using the 70m antennas of the DSN, at three locations. For communications near Earth, at both the beginning and end of each flight, the TDRSS satellites may be used for communications with the Mars vehicles.

Technical requirements for the Ka-band return links from Mars are given in Table 4. Because the Mars Relay Satellites (MRS's) are an essential element in the return path, requirements are shown for several paths from the Mars surface to the relay satellite. These paths have transmitter powers that are 2 W or less, and could be provided by SSPA's. Links to the DSN earth stations require from 14 to 180 W of transmitter power at Ka-band. These transmitters would likely be TWTA's. Antennas of 5 and 9m diameter are single beam, earth-pointing antennas which could be implemented as parabolic reflectors. The 1m antennas on the Mars relay satellites have the requirement for multiple, steerable beams, or scanning beams, to provide the necessary interconnects to the habitat, rovers, science instruments, and the various orbiting and transfer vehicles.

For Mars exploration, the relay satellites are required to serve as the switching and routing centers of the communications system infrastructure. Detection of the Ka-band modulated signals is required to extract specific signal routing information.

The data rates used in Table 4 for return signals from

Mars assume the existence and use of signal processing techniques to reduce the instrument and sensor output data rates to values that can be transmitted by practicable systems. 10 Mbps data returned from Mars requires about a 5m transmit antenna and 140 W of Ka-band transmitter power. The 100 Mbps required for conventional television quality and the 500 Mbps required for high definition television would require 10 and 50 times the transmitter power and/or antenna gain. Thus, for Ka-band communications from Mars in these two cases, data compression factors of 10 and 50 would be required to operate through the MRS-GT link shown in Table 4. For science imaging equipment or other high data rate sources similar reductions in data rates are required.

3.0 Ka-Band Technology Requirements and Needed Developments

For this paper, the nominal frequency used for Ka-band communications is assumed to be 32 GHz. The actual frequencies used may vary slightly because of constraints imposed by terrestrial frequency allocations, agreements among nations participating in space exploration, or because of technical considerations. But the general conclusions reached concerning the needs for Ka-band technology will be applicable to the actual frequencies used, provided they are within about ±20 percent of 32 GHz.

This section of the paper will discuss technologies of transmitters, antennas, and receivers operating at Ka-band, and will also discuss the technologies of network operations and on-board processors that impact on the Ka-band communication systems.

3.1 Ka-Band Transmitters

Tables 2, 3, and 4, presented earlier in this report summarize the transmitter power needs at Ka-band frequencies for the SEI program. For lunar exploration, transmitter powers range from 4 to 100 Watts for the return links to Earth. For Mars exploration, the range is from 0.5 to 180 Watts, with the lower end of the range used for transmissions in the vicinity of Mars. If one takes into account the mission timing, the Ka-band transmitter needs can be satisfied by the transmitter development schedules given in Table 5.

It is projected that the lower power transmitters not shown in Table 5, (0.5 W to 4 W) would be realizable in SSPA form when needed, with principally improvements in efficiency added to the current technology. (See reference 6 for state of the art efficiencies of Ka-band MMIC amplifiers.) The 15 W transmitters could be a TWTA based on the Cassini mission transmitter design (7 W, 43 per cent efficiency from Table 4.2 in reference 7). A greater technology development program would be needed to bring Impatt SSPA's to flight readiness at 15 W and at acceptable efficiency levels (currently 10 W, 10 per cent efficiency, from Table 4.3 in reference 7). The remaining transmitter needs could be satisfied with TWTA developments to meet the power levels and need dates. The development cycle from initial design to flight readiness typically takes 8 years. For Mars exploration transmitters, that are to be flown and used in lunar missions as part of the readiness testing, an additional two years would be added to the development cycle. Thus, a 50 W transmitter development would need to be initiated in 1995, and the 150 W transmitter in 2000. At the higher power levels, 50 W and above, the efficiency and the net electrical power consumption and heat dissipation become increasingly important. Efficiency improvement thus becomes a dominant thrust of the TWTA technology program. Further information on Ka-band TWTA technology is given in reference 8.

3.2 Ka-Band Antennas

Table 3 in section 2 shows no major technology developments needed for the single beam, parabolic antennas required for the lunar missions (maximum diameter equals 2 meters). For the Mars mission, Table 4 shows need for 5m and 9m antennas. A rigid 5m antenna would fit into a shuttle-sized launch vehicle and would require minimal development. However, a 5m deployable antenna and the 9m antenna (development required) would certainly require additional technology advancements (particularly in light of several recent difficulties with communications antenna deployments).

The greater technological challenge in Ka-band antennas results from the development of multibeam, scanning beam, or reconfigurable antennas to cover the myriad of communications targets as seen from a Mars relay satellite. (See figure 3.) For these applications, array antennas, with distributed MMIC (Monolithic Microwave Integrated Circuit) amplifiers would be one possible realization. Technology efforts to be undertaken now to meet the future antenna needs include MMIC amplifiers, phase shifters, array feed technology, array control and reconfiguration, and array architecture concepts. References 9 and 10 give some current developments in Ka-band arrays and array feeds. The proposed mission architectures include Mars relay satellites for the precursor missions with surface rovers launched in 2003 and 2005. Specific multibeam and/or scanning beam antenna technologies would need start-up in 1993.

3.3 Ka-Band Receivers

In the link calculations used to develop the requirements listed in Tables 3 and 4, Ka-band spacecraft receivers were assumed to have 2 dB noise figures. The DSN receivers were assumed to have ruby maser front ends with noise temperatures of 17K. The current state of the art in spacecraft receivers near 30 GHz is 3.4 dB noise figure as built for the ACTS satellite. (See reference 11.) Additional technology development in low noise GaAs amplifiers is needed to provide the targetted 2 dB noise figure. The DSN low noise Ka-band receiver is a planned DSN upgrade.

3.4 Ka-Band Network Components

The overall communications network concepts for the SEI program embody the principle of unattended network operations. The costs of the communications channels, the consequent limited bandwidth available, the competition for communications channels by science, vehicle, and crew needs, along with the long transmission delay times from Mars, and other technical factors all combine to require efficient use of the limited communications resource. The SEI scenarios require an unattended communications network, with automatic planning and scheduling, and with substantial buffer storage to maximize channel usage, without loss of data. This unattended network operations concept impacts the Ka-band components in the spacecraft. Ka-band switches are needed for signal routing. On board detection and remodulation, from Ka-band, down to baseband and back up are needed to implement the concept of remote message switching. Elements feeding Ka-band signals to the relay satellites are required to be controlled by a master planner/scheduler which may incorporate neural networks, expert systems, and artificial intelligence. In summary, the Ka-band communications systems for SEI generate requirements for subordinate technology developments in many areas including rf switches, modems, planner/schedulers, neural networks, and artificial intelligence. See reference 12 for current technology levels of network components.

4.0 Concluding Remarks

The proposed Space Exploration Initiative beginning in 1998 and continuing through 2020 and beyond requires wideband communications from the moon and Mars. Ka-band frequencies (near 32 GHz) can provide the long distance return links to the Earth and can provide surface and near-lunar and near-Mars communications networks. But technology developments and improvements are required to enable the necessary communications links. Major developmental areas are transmitters and antennas. Transmitter powers required range from 0.5 to 200 W. These may be solid state at lower power levels and travelling wave tube amplifiers at the higher levels. Near term technology development needs are a 15 W transmitter to be started now, and a 50 W transmitter to be started in 1995. Deployable 5m and 9m antennas are needed. To support Mars precursor missions, multi-beam and/or scanning beam antennas need technology development initiation in 1993.

Satellite receivers require noise figure improvement down to 2 dB, and the DSN upgrade to ruby maser front ends is required for the return of 10 Mbps signals from Mars.

The unattended communications networks envisioned for the exploration program require technology developments in rf switches, modems, neural networks, artificial intelligence, and planner/schedulers. To achieve full information transmission back from the moon and Mars, video and science image data compression are required to reduce the data transmission rates to be compatible with the transmitter power levels and antenna sizes given in this report.

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TABLE 1

Mission Timetable for Lunar and Mars Exploration
(Numbers in parentheses indicate number of missions that year)

	Moon Missions			Mars Missions		
Architecture	Precursor	Cargo	Piloted	Precursor	Cargo	Piloted
I. Mars Exploration	-	2005, 7, 8	2005, 6, 7, 9 (2)	1998, 2003, 2005	2012, 14	2014, 16
II. Science Emphasis for the Moon & Mars	1999, 2001	2006, 7, 8, 2010	2003, 4, 5, 6, 7 2009 (2), 10, 11, 13, 15	1998 (2), 2003, 2005, 7	2012, 14 2016, 18	2014, 16 2018, 20
III. Moon to Stay & Mars Exploration	2000 (2), 2002	2004, 5, 6, 7, 8 (2), 9, 10, ..., 18, 19, 20	2004, 5, 6 (2), 7 (3), 8 (3), 9 (4), 10 (3), 11 (3), 12 (3), ..., 18 (3), 19 (3), 20 (3)	1998 (2), 2003, 2005	2012, 14	2014, 16
IV. Space Resource Utilization	1999 (2), 2001	2003, 5, 7, 9, 2010	2004, 6, 8, 2010, 11 (2)	1998 (2), 2003, 2005	2014, 16	2016, 18

TABLE 2

Summary of Ka-Band Communications Applications for SEI

Objective	Missions	Time Frame	Communications Systems
Moon	Precursors	1999-2002	Ka-band
	Cargo and piloted	2003-2010	Ka-band, initial
		2010-2020	Ka-band, improved, or optical
Mars	Precursors	1998-2007	Ka-band with relay satellites
	Cargo and piloted	2012-2016	Ka-band, initial
		2016-2020	Ka-band, improved, or optical

TABLE 3

Return Link Characteristics for Lunar Exploration
(Nominal Frequency = 32 GHz, Receive Antenna Diameter = 34m.)

Communications Links	Missions	Data Rate (Mbps)	Transmit Power (W)	Transmit Antenna Diameter (m)
Science-GT	Precursor	0.5	4	0.1
Rover-GT	Piloted	20	13	0.35
LO-GT	Precursor	100	10	1
LTV-GT	Cargo+Piloted (Initial)	350	10	2
	Cargo+Piloted (Improved)	1000	35	2
LST-GT	Cargo+Piloted (Initial)	350	35	1
	Cargo+Piloted (Improved)	1000	100	1

Notes:

LO - Lunar Orbiter
GT - Ground Terminal
LST - Lunar Surface Transmitter
LTV - Lunar Transfer Vehicle

TABLE 4

Return Link Requirements for Mars Exploration
(Nominal Frequency = 32 GHz)

Communications Link	Missions	Data Rate (Mbps)	Transmit Power (W)	Transmit Antenna Diameter (m)	Receive Antenna Diameter (m)
MSO-GT	Precursor	1	14	5	70
MTV-GT	Cargo + Piloted (Initial)	10	140	5	70
MRS-GT	Cargo + Piloted (Initial)	10	140	5	70
	Cargo + Piloted (Improved)	40	180	9	70
Science-MRS	Cargo + Piloted (Initial)	0.5	0.5	0.1	1
	Cargo + Piloted (Improved)	20	2	0.3	1
Rover-MRS	Cargo + Piloted	20	2	0.3	1
HABITAT-MRS	Cargo + Piloted	10	1	0.3	1
HABITAT-GT	Cargo + Piloted	10	140	5	70

Notes:

MSO - Mars Science Orbiter
GT - Ground Terminal
MTV - Mars Transfer Vehicle
MRS - Mars Relay Satellite

TABLE 5

Ka-Band Transmitter Requirements and Schedule

Transmitter Power	Launch Readiness Date	Technology Development Initiation
15W	1998	NOW!!
50W	2003	1995
150W	2010	2000
200W	2016	2008

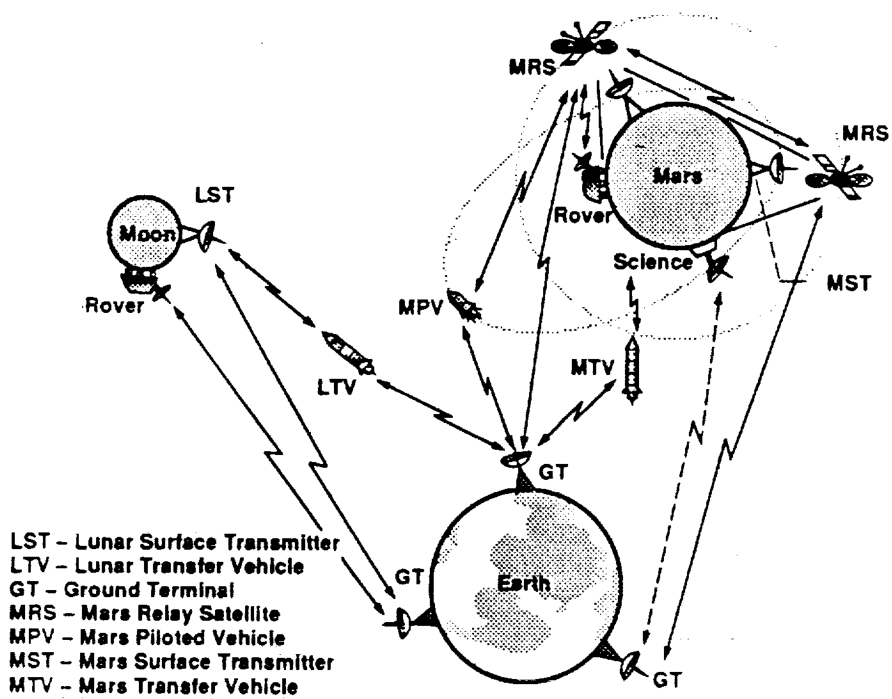

Figure 1. — Lunar/Mars Communications Network.

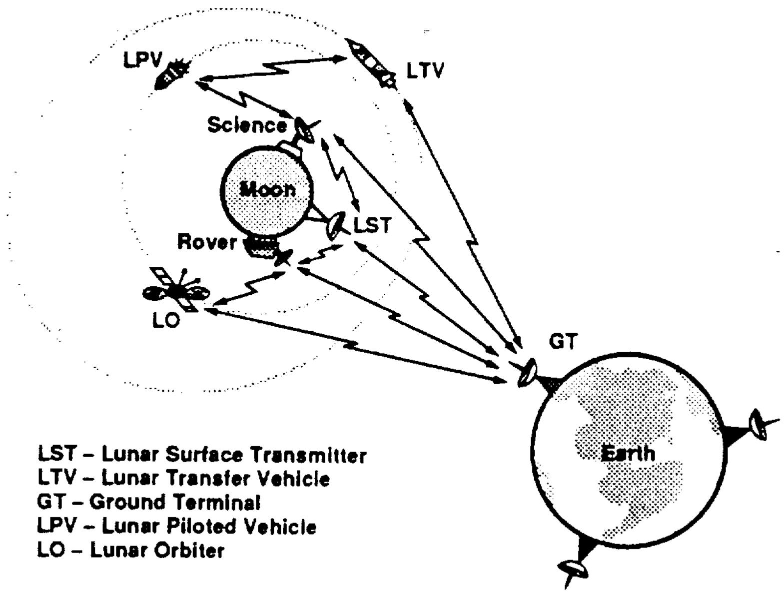

Figure 2. — Ka – Band Communications Return Links for Lunar Exploration.

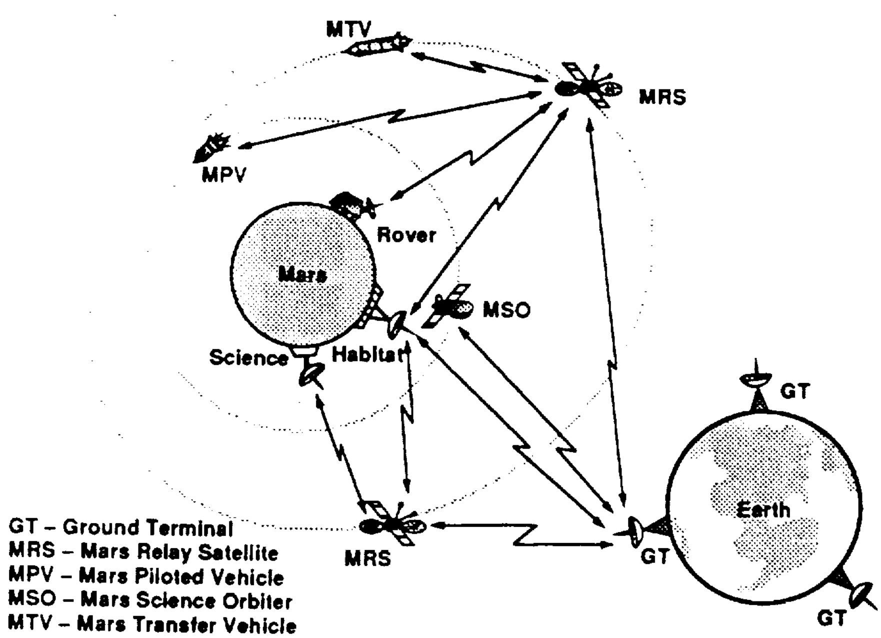

Figure 3. — Ka – Band Communications Return Links for Mars Exploration.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	1991	Technical Memorandum

4. TITLE AND SUBTITLE
Overview of Ka-Band Communications Technology Requirements for the Space Exploration Initiative

5. FUNDING NUMBERS
WU-316-30-19

6. AUTHOR(S)
Edward F. Miller

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-6661

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-105308
AIAA-91-3424

11. SUPPLEMENTARY NOTES
Prepared for the Conference on Advanced Space Exploration Initiative Technologies cosponsored by AIAA, NASA, and OAI, Cleveland, Ohio, September 4-6, 1991. Responsible person, Edward F. Miller, (216) 433-3479.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 91

12b. DISTRIBUTION CODE

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14. SUBJECT TERMS
Communications technology; K-Band; Exploration; Space exploration initiative

15. NUMBER OF PAGES
10

16. PRICE CODE
A02

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	