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Research and Development of Laser Diode Based Instruments for Applications in Space

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Abstract. Laser diode technology continues to advance at a very rapid rate due to commercial applications such as telecommunications and data storage. The advantages of laser diodes include, wide diversity of wavelengths, high efficiency, small size and weight and high reliability. Semiconductor and fiber optical-amplifiers permit efficient, high power master oscillator power amplifier (MOPA) transmitter systems. Laser diode systems which incorporate monolithic or discrete (fiber optic) gratings permit single frequency operation. We describe experimental and theoretical results of laser diode based instruments currently under development at NASA Goddard Space Flight Center including miniature lidars for measuring clouds and aerosols, water vapor and wind for Earth and planetary (Mars Lander) use.

INTRODUCTION

Laser diode technology continues to evolve due to widespread commercial applications in telecommunications, consumer electronics, medicine and industrial processing. In this paper , we present recent advances on the use of laser diodes as transmitter sources for instruments in space. A lidar system based on small and highly efficient semiconductor lasers is now feasible due to recent developments in the laser and detector technologies. The recent development of high detection efficiency (50%), silicon-based photon-counting detectors (Dautet, 1993), when combined with high laser pulse repetition rates and long receiver integration times make miniature lidar systems feasible. Aerosol lidar systems using this technique have been demonstrated for both Q-switched, diode-pumped solid-state laser transmitters (532 nm) (Spinhirne, 1993)and semiconductor diode lasers (832 nm) (Rall, 1995). In this paper, we present results on the development of miniature lidars for atmospheric water vapor and wind profiling.

WATER VAPOR LIDAR

NASA is developing a miniature lidar (Abshire, 1995) instrument for the remote sensing of Martian atmospheric water vapor from the surface of Mars. The 935.68 nm wavelength has been chosen for the instrument operating wavelength since strong water vapor absorption lines, high electrical efficiency lasers and high quantum efficiency photon counting detectors are all available in this region. The laser diode oscillator approaches are, (1) a distributed Bragg reflector (DBR) laser diode, (2) a Distributed FeedBack laser diode and, (3) a Fabry-Perot laser diode with external cavity fiber grating feedback. In addition, we are using an InGaAs semiconductor flared amplifier to provide higher power for the diode laser approaches in a discrete master-oscillator power-amplifier (MOPA) configuration.

For approach (1), ridge waveguide (RW) InGaAs distributed Bragg reflector (DBR) laser diodes have been under development at the University of Illinois. Initial results at ~990 nm wavelength produced diodes with 39 kHz spectral linewidth and 24 mW CW power. Similar DBR lasers have been developed at for use at 935 nm (Roh, 1997). Figure 1 shows the water vapor spectra near 935 nm as scanned by current tuning the 935 nm DBR laser diode.

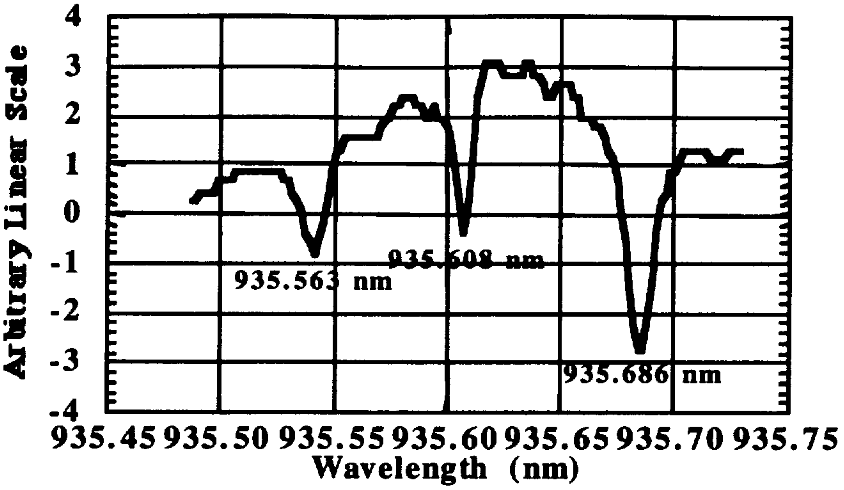

FIGURE 1. Water vapor absorption lines scanned in the 935 nm region by current tuning of the 935 nm DBR laser described in (Roh, 1997).

For approach (2) an aluminum free InGaAsP distributed feedback (DFB) laser is under development by Sensors Unlimited Inc. (subcontract to Sarnoff Lab). Similar AlGaAs DFB laser diodes have been previously developed at the 935 nm wavelength (Martin, 1995).

In approach (3), a Sensors Unlimited Inc. Model SU 935 CD FP 50 mW Fabry-Perot InGaAs laser diode was coupled to a 3M Inc. fiber optic grating with a 935.4 nm center wavelength at 25 C, a 0.1 nm bandpass and 7% reflectivity. The laser and fiber grating were temperature tuned to the water vapor absorption line at 935.68 nm. This laser was used to make a real time measurement of the water vapor absorption line profile over a 16 meter free space optical path (Krainak, 1997). We have submitted a patent application (Krainak, 1998) for methods of achieving single frequency operation of Fabry-Perot laser diodes using fiber grating feedback.

Higher power pulsed operation is required to obtain range resolved atmospheric water vapor profile measurements. We constructed a semiconductor master oscillator power amplifier (MOPA) laser consisting of a bulk grating

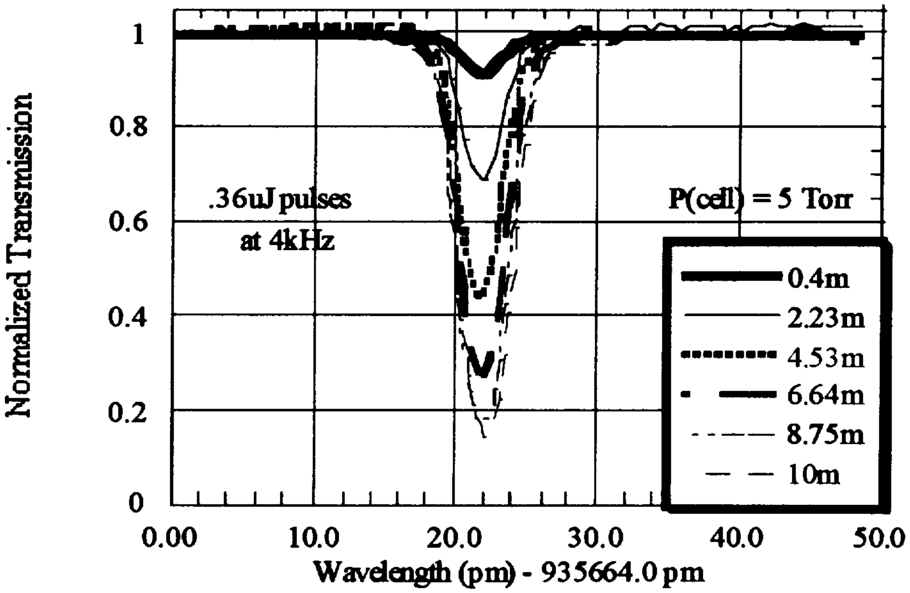

FIGURE 2. Water vapor absorption line scanned with pulsed diode amplifier seeded with output of a bulk grating external cavity diode laser.

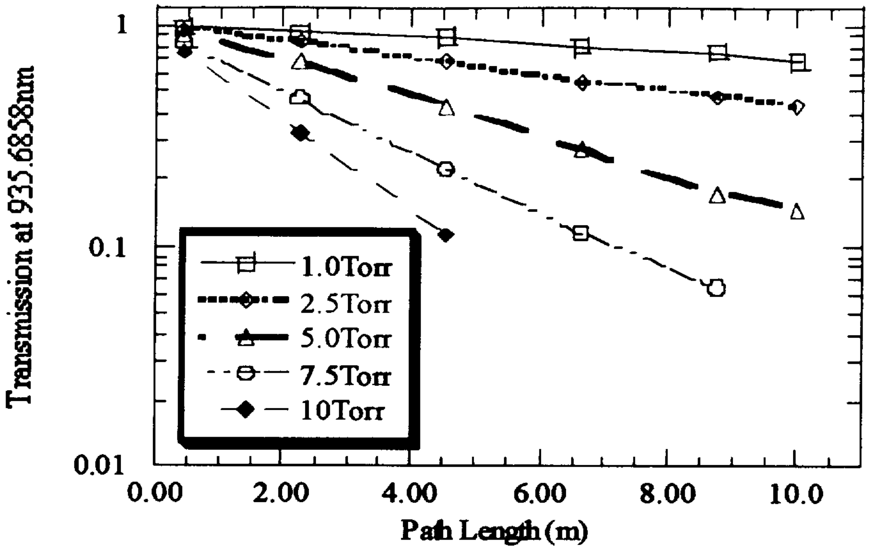

FIGURE 3. Transmission vs. path length and pressure for the 935 nm water vapor absorption line

external cavity diode laser (ECDL) master oscillator and a modulated SDL Inc. Model 8630-E InGaAs flared amplifier.

Figure 2 shows the 935 nm water vapor absorption line scanned with the discrete MOPA laser transmitter at various path lengths while at low pressure (5 Torr). The semiconductor amplifier was pulsed at a 4 kHz repetition rate. Similar spectra were measured using the MOPA transmitter at pressures of 0.5, 1.0, 2.5, 7.5, and 10 Torr for several path lengths. Figure 3 shows that log of the transmission at line center varies linearly with path length in agreement Beers law. In these experiments, our water vapor measurement sensitivity (2.5% absorption at 1 Torr - corresponding 100 ppm) was limited by receiver noise. We plan to use a photon counting receiver to better quantify our instrument sensitivity performance limits.

These water vapor absorption spectra measurements demonstrate the capability for a miniature Differential Absorption Lidar (DIAL) instrument. In a related effort, we are assisting the National Oceanic and Atmospheric Administration (NOAA) with the development of a miniature water vapor DIAL instrument (Machol, 1998) operating at 825 nm wavelength for ground based Earth atmospheric water vapor measurements.

WIND LIDAR

We have been investigating a semiconductor-laser-based lidar system which uses the "edge-filter" direct detection technique (Korb, 1992) to infer Doppler frequency shifts of signals backscattered from aerosols in the planetary boundary layer (PBL). Our miniature wind lidar incorporates a novel semiconductor laser design which mitigates the deleterious effects of frequency chirp in pulsed diode lasers, a problem which has limited their use in such systems in the past. Our miniature lidar could be used on a future Mars lander and in terrestrial applications due to low cost, small size, weight and power.

The configuration of the experimental system is given in Figure 1. The heart of the lidar system is the laser, which is a novel semiconductor master oscillator-power amplifier (MOPA) laser design which practically eliminates the deleterious effects of frequency chirp when the laser is pulsed. The master oscillator is a CW 150 mW, fiber-coupled distributed Bragg reflector (DBR) laser with a measured linewidth of less than 10 MHz (Major, 1994). The MO light is coupled into a high-power tapered amplifier (SDL Model 8630-E). The MO light strongly saturates the gain of the PA such that the refractive index is "clamped" even under current pulsing which eliminates frequency chirp. The linewidth of the MOPA under pulsed conditions is measured to be less than 10 MHz.

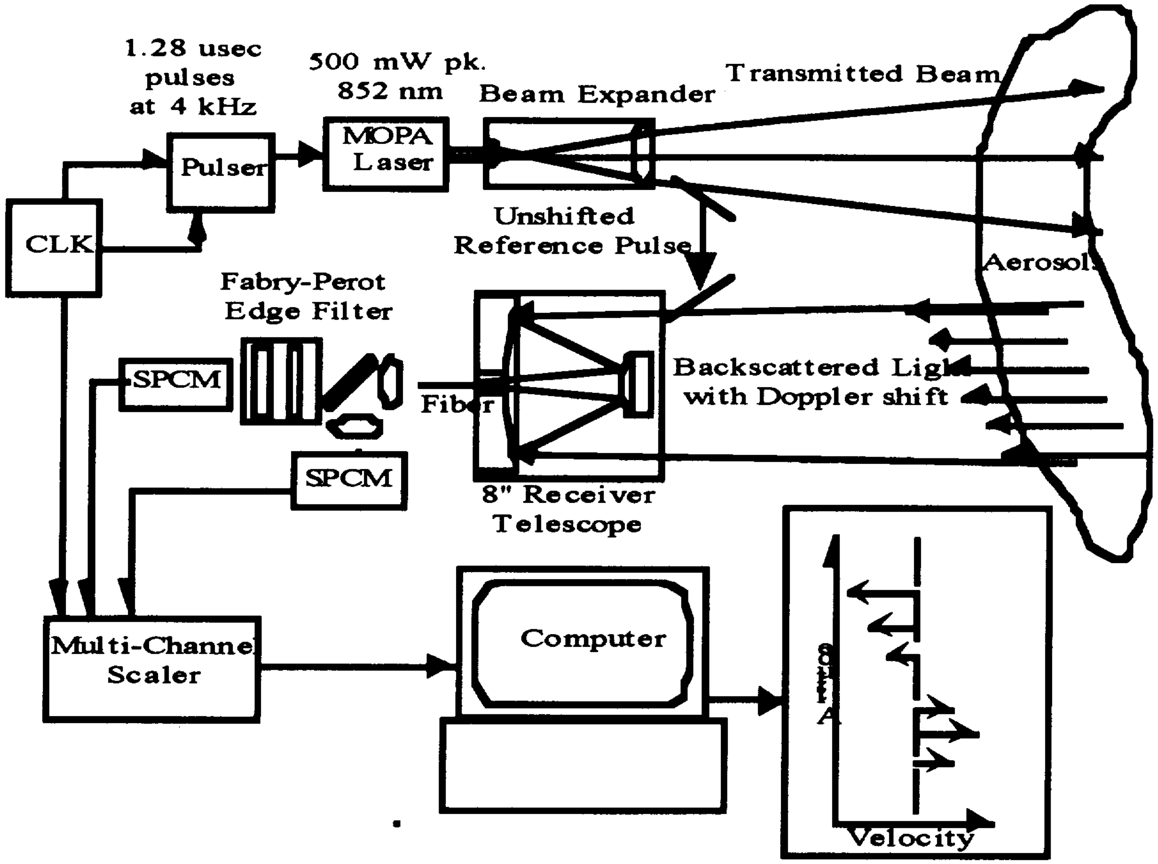

FIGURE 4. Schematic of miniature wind lidar profiler.

The beam from the pulsed diode laser transmitter is expanded and propagated out into the atmosphere. A small fraction of the transmitter beam is intercepted by the edge of a solid retro-reflector and coupled directly into the telescope and receiver optics to serve as the reference (REF) beam. The backscattered return from the atmosphere is collected with an inexpensive "amateur-astronomer"-grade Meade 8" diameter (203 mm), F/6.3 Schmidt-Cassegrain telescope. The telescope is mounted on a tripod and pointed 45 degrees above the horizon for wind measurements. The telescope aft optics focus the light into 100 meters of multi-mode fiber for delivery to the receiver system, which is kept within the laboratory. Once at the receiver, the signal photons from the fiber are collimated and transmitted through the edge filter. A portion of these photons are split off with a 70/30 beamsplitter and sent to the energy monitor detector for normalization. The central fringe of a Fabry-Perot interferometer (FPI) etalon filter is used as our edge filter. An FPI edge filter was selected over other types of edge filters due to its tunability, high transmission efficiency, and high frequency resolution. The optimal width of our FPI is 100 MHz, which as calculated in the previous section results in a maximum edge sensitivity of 4.6% per m/sec of radial velocity. Both the EM and FPI channel signals are collected and focused back into multimode fibers for delivery to the detectors. Narrow bandpass filters are placed before each channel to eliminate the background noise. The EM and FPI channel photon-counting detectors are based on silicon avalanche photo-diodes (APDs), which are operated in "Geiger" mode by application of a high voltage. Both detectors are multi-mode fiber coupled, which allows for ease of use and greater protection from high-signal damage. Each detector contains a built-in signal discriminator which produces a TTL pulse for each photo-electron count; no additional amplification is therefore required. The detector signal counts for both channels are histogrammed as a function of arrival time using two multi-channel scalars (MCS). The temporal width of each range bin is matched to that of the initial laser pulse and dictates the corresponding range resolution and vertical resolution. The pulse rate determines the maximum altitude above ground level (AGL). For atmospheric measurements, the lidar will transmit laser pulses and integrate the return signal until a threshold SNR is achieved in a particular range bin. The total number of counts in any given range bin is comprised of the return signal counts and the background and detector dark counts; the average number of background and dark counts is determined by measuring the total counts in the last 10 range bins, where it is assumed that the amount of signal present in these bins is negligible due to their corresponding long range. The frequency of the signal in any given range bin is determined by first subtracting the measured background and dark counts, then dividing the number of signal counts

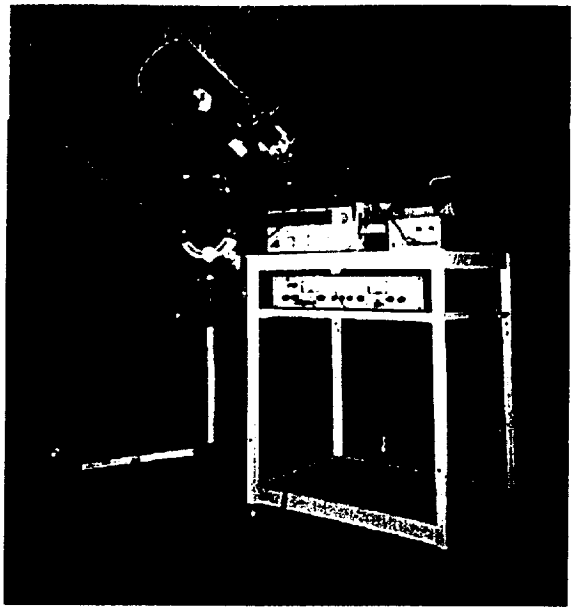

FIGURE 5. Photograph of miniature wind lidar profiler.

histogrammed for that bin in the FPI MCS by the number of signal counts in the same bin in the EM MCS. The calibration constant is applied to determine the normalized edge transmission of each range bin. The measured counts in the first range bin correspond to the unshifted reference laser pulse (REF), and the normalized edge transmission for the REF bin determined in the same manner. This is also used as the error signal for a servo loop to lock the laser frequency to the 50% transmission point of the FPI edge filter. Once normalized, the edge transmission in the REF bin is compared to all of the SIG bins to determine the change in normalized transmission, ΔI_N. This information is then used with the knowledge of the edge filter slope to determine the relative Doppler frequency shift $\Delta \nu_{Doppler}$ as given in (1). The velocity is then simply determined using (2), and the computer plots the measured velocity of each range bin as a function of altitude above ground level (AGL). Error bars on each measurement are added, based on the measured signal-to-noise ratio. The measurement is repeated in an orthogonal direction to determine the vector velocity of the wind.

A miniature lidar wind profiler has been designed and characterized in the laboratory. A photograph of the present miniature wind lidar profiler system is shown in Figure 5. The system is based on compact and efficient semiconductor lasers which could enable the use of such a lidar on Mars. Our results indicate that the MLWP could measure wind velocity profiles accurately within the terrestrial planetary boundary layer under night-time conditions. Daylight operation could be achieved by scaling of the laser transmitter power and decreasing the receiver bandpass transmission.

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PRELIMINARY PROGRAM

SPACE TECHNOLOGY & APPLICATIONS INTERNATIONAL FORUM (STAIF - 99)

" Opportunities and Challenges for the New Millenium"

January 31-February 4, 1999, Albuquerque Hyatt Hotel, NM

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CONFERENCE ON GLOBAL VIRTUAL PRESENCE

CONFERENCE ON APPLICATION OF THERMOPHYSICS IN MICROGRAVITY & BREAKTHROUGH PROPULSION PHYSICS

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SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM (STAIF-99)

PERIOD/DAY	SUNDAY, JANUARY 31, 1999							
4:30-7:30p.m.	**STAIF REGISTRATION**, 2nd Floor, Albuquerque Hyatt Regency Hotel							
7:00-8:00p.m.	**STAIF "GET ACQUAINTED" HOUR (Snack)**							
	MONDAY, FEBRUARY 1, 1999							
6:45-7:45a.m.	**Speaker's Breakfast**							
8:00-8:15a.m.	**WELCOMING AND OPENING REMARKS** Pavilion I, II, and III							
8:15-9:45a.m.	**PLENARY SESSION I:** ***VIEWS FROM THE TOP*** Pavilion I, II, and III							
9:45-10:15a.m.	**Coffee Break** – Exhibit Area (Pavilion IV, V, and VI) **Press Conference -**							
10:15-11:45p.m.	**PLENARY SESSION II:** ***PROGRAMS AND TECHNOLOGY*** Sendero Ballroom							
11:45-1:45p.m.	**STAIF-99 LUNCHEON**, Pavilion I, II, and III							
	TECHNICAL SESSIONS							
ROOM	Sendero Ballroom (I) (175 capacity)	Sendero Ballroom (III) (180 capacity)	Sendero Ballroom (II) (125 capacity)	Enchantment Ballroom (E & F) (120 capacity)	Enchantment Ballroom (A & B) (120 capacity)	Fiesta Room (I & II) (80 capacity)	Fiesta Room (III & IV) (80 capacity)	Enchantment Ballroom (C & D) (100 capacity)
1:45-3:45p.m.	Conference on Global Virtual Presence Opening Session	RESEARCH CAPABILITIES OF THE INTERNATIONAL SPACE STATION (A1) Opening Session	16th Symposium on Space Nuclear Power and Propulsion Opening Session	Conference on Applications of Thermophysics in Microgravity & Breakthrough Propulsion Physics Opening Session	Conference on Next Generation Launch Systems Opening Session			
3:45-4:00p.m.	**Coffee Break** – Exhibit Area (Pavilion IV, V, and VI)							
4:00-6:00p.m.	TECHNICAL INTERCHANGE ON SPACE STATION CAPABILITIES FOR EXTERNAL PAYLOADS & OBSERVATIONAL PAYLOADS (A2)	FLUIDS AND COMBUSTION RESEARCH ON THE ISS (A3)	LASERS IN SPACE I (B1)	AFFORDABLE SPACE FISSION POWER AND PROPULSION (E1)	PROJECT COST, OPERATIONS AND MANAGEMENT (D1)	FUNDAMENTALS OF MICROGRAVITY TWO-PHASE FLOW AND HEAT TRANFER (C1)		COMMUNICATION AND SOLAR ENERGY COLLECTION TECHNOLOGIES I (B2)
6:30-8:00p.m.	**STAIF-99 RECEPTION**, Pavilion I, II, and III							

A = Conference on International Space Station Utilization
B = Conference on Global Virtual Presence
C = Conference on Applications of Thermophysics in Microgravity and Breakthrough Propulsion Physics
D = Next Generation Launch Systems
E = 16th Symposium on Space Nuclear Power and Propulsion

SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM (STAIF-99)

PERIOD/DAY	TUESDAY, FEBRUARY 2, 1999							
6:45-7:45a.m.	**Speaker's Breakfast**							
8:00-9:45a.m.	**PLENARY SESSION III**: ***MICRO SATELLITES, Nano Satellites and MEMS Technology*** Pavilion I, II, and III							
9:45-10:15a.m.	**Coffee Break – Exhibit Area (Pavilion IV, V, and VI)**							
	TECHNICAL SESSIONS							
ROOM	Sendero Ballroom (I) (175 capacity)	Sendero Ballroom (III) (180 capacity)	Sendero Ballroom (II) (125 capacity)	Enchantment Ballroom (E & F) (120 capacity)	Enchantment Ballroom (A & B) (120 capacity)	Fiesta Room (I & II) (80 capacity)	Fiesta Room (III & IV) (80 capacity)	Enchantment Ballroom (C & D) (100 capacity)
10:15-12:15p.m.	SPACE SCIENCES ON THE ISS: TRUSS PAYLOADS (A4)	EARTH SCIENCE & REMOTE SENSING ON THE ISS I (A5)	LASERS IN SPACE – II (B3)	ADVANCED CONCEPTS (E2)	LAUNCH VEHICLE TECHNOLOGIES I (D2)	APPLICATIONS OF TWO-PHASE THERMAL CONTROL SYSTEMS FOR SPACE (C2)		COMMUNICATION AND SOLAR ENERGY COLLECTION TECHNOLOGIES II (B4)
12:15-1:15p.m.	**LUNCH BREAK AND TECHNICAL PROGRAM MEETINGS**							
1:15-3:15p.m.	SPACE SCIENCES ON THE ISS: JEM PAYLOADS (A6)	EARTH SCIENCE & REMOTE SENSING ON THE ISS II (A7)	OVERVIEW OF SOME ISS BUSINESS INVESTMENTS & COMMITMENTS THROUGH THE COMMERCIAL SPACE CENTER PROGRAM (A8)	REDUCING THE COST OF MARS EXPLORATION (E3)	ENERGY CONVERSION: AMTEC TECHNOLOGY I (E4)	IN-ORBIT EXPERIMENTS WITH CAPILLARY PUMPED LOOPS & LOOP HEAT PIPES (C3)		COMMUNICATION AND SOLAR ENERGY COLLECTION TECHNOLOGY III (B5)
3:15-3:30p.m.	**Coffee Break – Exhibit Area (Pavilion IV, V, and VI)**							
3:30-5:30p.m.	SPACE SCIENCES ON THE ISS: ACCESS (A9)	COMMERCIAL COMMUNICATION SYSTEMS FOR THE ISS (A10)	SPACE AUTONOMY (B6)	STUDIES OF COMPONENTS OF THE AMTEC ELECTRO-CHEMICAL CELL: ELECTRODES, DLECTROLYTE & CURRENT COLLECTOR (E5)	LAUNCH VEHICLE PROPULSION (D3)	MICROGRAVITY FLUID PHYSICS RESEARCH (C4)	FUSION (E6)	ENERGY CONVERSION AND HIGH TEMPERATURE MATERIALS (B7)

INDUSTRIAL HOSPITALITY SUITES, 7:00p.m. – 10:00p.m.

A = Conference on International Space Station Utilization
B = Conference on Global Virtual Presence
C = Conference on Applications of Thermophysics in Microgravity and Breakthrough Propulsion Physics
D = Next Generation Launch Systems
E = 16th Symposium on Space Nuclear Power and Propulsion

SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM (STAIF-99)

PERIOD/DAY	WEDNESDAY, FEBRUARY 3, 1999
6:45-7:45a.m.	**Speaker's Breakfast**
8:00-9:45a.m.	**PLENARY SESSION IV**: ***INTERNATIONAL PANEL ON COLLABORATION IN THE USE OF THE ISS*** Pavilion I, II, and III
9:45-10:15a.m.	**Coffee Break – Exhibit Area (Pavilion IV, V, and VI)**

TECHNICAL SESSIONS

ROOM	Sendero Ballroom (I) (175 capacity)	Sendero Ballroom (III) (180 capacity)	Sendero Ballroom (II) (125 capacity)	Enchantment Ballroom (E & F) (120 capacity)	Enchantment Ballroom (A & B) (120 capacity)	Fiesta Room (I & II) (80 capacity)	Fiesta Room (III & IV) (80 capacity)	Enchantment Ballroom (C & D) (100 capacity)
10:15-12:15p.m.	SPACE SCIENCES ON THE ISS: OTHER TOPICS (A11)	EARTH SCIENCE & REMOTE SENSING ON THE ISS III (A12)	MINIATURIZATION TECHNOLOGIES I (B8)	MSP '98 CPL – LESSONS LEARNED SPECIAL SESSION	COMMERCIALIZATION OF LAUNCH SYSTEMS (D4)	SAFETY AND LAUNCH APPROVAL PROCESS (E7)		ENERGY CONVERSION: AMTEC TECHNOLOGY II (E8)
12:15-1:15p.m.	**LUNCH BREAK**							
1:15-3:15p.m.	SPACE SCIENCES ON THE ISS (A13)	EARTH SCIENCE & REMOTE SENSING ON THE ISS IV (A14)	MINIATURIZATION TECHNOLOGIES II (B9)	FUTURE MICROGRAVITY THERMO-PHYSICS RESEARCH & DEVELOPMENT (C5)	ADVANCED/ NOVEL CONCEPTS (D5)	ADVANCED RADIOISOTOPE POWER SYSTEMS (E9)		ENERGY CONVERSION: TERRESTRIAL APPLICATIONS OF SPACE TECHNOLOGY (E10)
3:15-3:30p.m.	**Coffee Break – Exhibit Area (Pavilion IV, V, and VI)**							
3:30-5:30p.m.	GRAVITATIONAL BIOLOGY ON THE ISS (A15)	INNOVATIVE APPROACHES TO COMMERCIAL ACTIVITIES ON THE ISS: What can the Private Sector do? (A16)	SPACE WEATHER (B10)	EMERGING PHYSICS TOWARD HYPER-FAST SPACE TRAVEL I (C6)	D SESSION (D6)	THERMAL TO ELECTRIC CONVERSION TECHNOLOGIES (E1)		THERMIONIC TECHNOLOGY AND APPLICATIONS I (E12)
6:30-8:00p.m.	**SPECIAL SESSION**: Space Enterprise – Discussion on where we are and where we are going. (Light Snack will be Served)							

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SPACE TECHNOLOGY AND APPLICATIONS INTERNATIONAL FORUM (STAIF-99)

PERIOD/DAY	THURSDAY, FEBRUARY 4, 1999							
6:45-7:45a.m.	**Speaker's Breakfast**							
ROOM	Sendero Ballroom (I) (175 capacity)	Sendero Ballroom (III) (180 capacity)	Sendero Ballroom (II) (125 capacity)	Enchantment Ballroom (E & F) (120 capacity)	Enchantment Ballroom (A & B) (120 capacity)	Fiesta Room (I & II) (80 capacity)	Fiesta Room (III & IV) (80 capacity)	Enchantment Ballroom (C & D) (100 capacity)
8:00-10:00a.m.	BIOMEDICAL RESEARCH ON THE ISS (A17)	ENGINEERING RESEARCH & TECHNOLOGY DEVELOPMENT: ISS AS AN ENGINEERING TESTBED (A18)	SPACE PROTECTION I (B11)	EMERGING PHYSICS TOWARD HYPER-FAST SPACE TRAVEL II (C7)	D SESSION (D7)	NUCLEAR SURFACE POWER SYSTEMS (E13)	THERMAL PROPULSION (E14)	SPECIAL HEAT PIPES (C8)
10:00-10:15a.m.	**Coffee Break – Exhibit Area (Pavilion IV, V, and VI)**							
10:15-12:15p.m.	BIO-TECHNOLOGY ON THE ISS (A19)		SPACE PROTECTION II (B12)	EMERGING PHYSICS TOWARD BREAK-THROUGH SPACECRAFT POWER (C9)	LAUNCH VEHICLE TECHNOLOGIES II (D8)	POWER BEAMING I (E15)		ENERGY CONVERSION: GENERAL (E16)
12:15-1:15p.m.	**LUNCH BREAK**							
1:15-3:15p.m.	MATERIALS RESEARCH ON THE ISS (A20)	ENGINEERING RESEARCH & TECHNOLOGY DEVELOPMENT: ENGINEERING EXPERIMENTS ON THE ISS (A21)	REMOTE SENSING I (B3)	EMERGING PHYSICS TOWARD PROPELLANT-LESS PROPULSION-I (C10)		RADIOISOTOPE POWER SYSTEM PRODUCTION (E17)		THERMIONIC TECHNOLOGY AND APPLICATIONS II (E18)
3:15-3:30p.m.	**Coffee Break**							
3:30-5:30p.m.	SPECIAL TOPICS IN ISS UTILIZATION (A22)	SPACE STATION PLANNING – NASA'S SBIR PROGRAM HIGHLIGHTS (A23)		EMERGING PHYSICS TOWARD PROPELLANT-LESS PROPULSION II (C11)		POWER BEAMING II (E19)		COMMERCIAL ISSUES WITH THE USE OF SPACE NUCLEAR POWER (E20)

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