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LIDAR TECHNOLOGY MEASUREMENTS AND TECHNOLOGY: REPORT OF PANEL

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Lidar is ready to make an important contribution to tropospheric chemistry research with a variety of spaceborne measurements that complement the measurements from passive instruments. Over the last two decades, the development of lidar techniques and systems has evolved to the point where it is being used in many different atmospheric investigations from ground, airborne, and balloon platforms. Lidar can now be considered for near-term and far-term space missions dealing with a number of scientifically important issues in tropospheric chemistry. Measurements that can be made by a spaceborne lidar system include distributions of aerosols and gases using the active remote sensing techniques previously discussed. Since there is a scarcity of data on the global distribution of tropospheric species such as O_3, H_2O, and aerosols, a lidar system in space could make a valuable contribution in conducting tropospheric investigations in conjunction with passive remote measurements of the same or complementary species. In this section, we will address the evolution in the lidar missions from space. Details of these missions are given in table VIII, which is based on the information generated by the Lidar Measurement and Technology Working Group report and on the report by E. V. Browell (both of which are presented in this document).

Three time periods were considered in the evolutionary development. In the near-term period of Space Shuttle flights in 1990 and EOS missions after 1993, lidar measurements of aerosols, H_2O, and O_3 distributions can be made in the troposphere. A single wavelength lidar system operating from 0.5-1.0 μm can provide measurements of aerosol structure through the troposphere with a vertical resolution of <0.5 km. These data contain information on planetary boundary-layer depth, stable layers in the free troposphere, cloud heights, and other inferred meteorological parameters. A multiple wavelength lidar measurement of aerosols can also provide some information on aerosol size distributions which may be used to identify the type of aerosols being detected. In this time period, a DIAL system may be flown to investigate mid-to-lower tropospheric H_2O globally. The H_2O DIAL measurements will include H_2O column content and vertical profiles with 1 to 2 km resolution. Measurements of O_3 column content in the troposphere and O_3 profiles with 2 km vertical resolution can also be made. DIAL measurements of H_2O and O_3 are made simultaneously with aerosol distribution measurements at the off-line wavelength.

The second period in the evolution of laser remote sensing from space would include possible Space Shuttle flights in the mid 1990's, with an EOS mission by 1997. This requires that the lidar/DIAL technique and technology be ready by about 1992. For this period, we expect to make spaceborne H_2O DIAL measurements with 1 km vertical resolution throughout the troposphere during the day and night. The column

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content of NH_3 can be obtained using an IR DIAL measurement, and temperature can be measured with an O_2 DIAL technique with about 1 km vertical resolution. It is noted that all of the lidar measurement capability noted for the initial period is also available for this period.

The third period, from 2005-2010, includes future DIAL measurements from space of trace species that currently have only been done at elevated levels in the troposphere with low-power DIAL systems. With expected developments in laser systems, it is possible to envision spaceborne DIAL column content measurements of NO_2, SO_2, NO, CH_4, CO, and, possibly, H_2O_2.

INTRODUCTION: REQUIRED LIDAR DEVELOPMENT AND MEASUREMENTS

The use of a lidar system for the remote sensing of a tropospheric species from space requires advances in laser and detector technology and in supporting spectroscopic and lidar atmospheric measurements. These advances are dependent upon the type of lidar system that is being considered and the time frame for the expected implementation of the lidar or DIAL system for both Space Shuttle and EOS applications. This time frame has been broken into three categories--designated by I, II, and III--which represent, respectively, near term (1986-1992), long term (1990-2000), and those techniques in the far future which will require a significant technology breakthrough to be realized.

Using these criteria, the lidar panel produced two compendiums of their assessment of laser and lidar technology and an approximate listing of the expected time that such lasers would be available for space missions. The first compendium consisted of worksheets that describe the technical details for the laser remote sensing of each atmospheric constituent. The technical issues addressed include laser availability, optical detection sensitivity, and a listing of the most serious technical issues. These worksheets were used to compile a second compendium on the lidar technology assessment, which is a summary of the results from the worksheets. This "summary" assessment is given in the following section.

SUMMARY OF LIDAR TECHNOLOGY ASSESSMENT

Table IX is an assessment of laser availability for space missions based upon the technical data to be given in the worksheets presented.

The time frame for using each type of laser is given for missions on the Space Shuttle and on EOS with low and high duty cycles. For example, water vapor measurements could be conducted using an Alexandrite laser on the Space Shuttle by 1990, EOS (with 10-percent duty cycle) by 1993, and on EOS with long life by 1997. A continuous-wave (CW) CO_2 laser is felt to be able to measure the column content of water vapor from the Space Shuttle and EOS in the same time frames. Aerosols and clouds and Excimer-based O_3 measurements are the only other lidar applications that may be available by 1993 for EOS. By 1997, the measurement of NH_3 may be possible from EOS, using a CO_2 laser system. Long-life DIAL investigations of H_2O, O_3, and NH_3 may be conducted from EOS in the late 1990's. Measurements of CO, CH_4, NO, NO_2, SO_2, and H_2O_2 from space will be paced by the development of suitable lasers. It is expected that DIAL measurements of these species from EOS will be ready in the 2010 time frame.

It is informative to group these missions by the indicated time frames, and then list the most stressing technical issues for the development of spaceborne lidar systems. These may be expressed as follows.

Phase I: Near-Term Technology Development and Measurements

A. Aerosol Lidar

1. Need high-altitude feasibility demonstration of lidar detection of tropospheric aerosols using Nd:YAG, Excimer, or Alexandrite lasers.
2. Increase efficiency and lifetime of flashlamp pumped Nd:YAG and Alexandrite lasers and discharge Excimer laser.
3. Develop high-efficiency diode pumped solid-state lasers.

B. H_2O DIAL Detection (Column Content)

1. Develop high-resolution Alexandrite laser for DIAL use.
2. Demonstrate DIAL capability at high altitude.
3. Study and develop use of CW CO_2 homodyne (heterodyne) lidar for water vapor detection.

C. O_3 DIAL Detection (Column Content)

1. Demonstrate use of Excimer laser DIAL system at high altitude (>80 km) for tropospheric O_3 detection.
2. Study use of homodyne (heterodyne) CO_2 DIAL for O_3 column content measurements.

Phase II: Long-Term Technology Development and Measurements

A. H_2O Range-Resolved Measurements

1. Increase power and efficiency of Alexandrite laser for H_2O measurements.
2. Study use of Nd:GLASS and Raman shifted technology for upper tropospheric H_2O profiling.
3. Develop diode-pumped tunable solid-state lasers.

B. NH_3 Measurements

1. Develop CW CO2 heterodyne DIAL for column content NH_3 measurements.

C. NH_3 Temperature Measurements

1. Develop high-resolution Alexandrite laser with precision wavelength control for temperature measurements.

Phase III: Technology Breakthrough Required

A. CH_4, NO, NO_2, and H_2O_2 Measurements

1. These molecules have absorption spectra in spectral regions where current lasers do not have sufficient power for remote sensing purposes and current attempts to reach such wavelengths at high power have not, as yet, been fruitful. However, some new laboratory frequency shifting techniques do hold promise. These include Raman shifting of an Excimer laser and stimulated electronic Raman shifting in cesium vapor using a frequency doubled Alexandrite laser.

B. SO_2

1. SO_2 can be detected in the atmosphere using a UV laser source, but only at very high concentrations such as that emitted by a power plant plume. The optical depth of SO_2 under normal conditions may be too low to permit detection in the ambient troposphere.

C. CO

1. The detection of CO requires a 4.7 μm laser source. Frequency shifting techniques hold promise in reaching this spectral region, but much future work is required before high laser powers will be realized.

TABLE VIII.- PROPOSED EVOLUTION OF LIDAR SPACE MISSIONS

Period	Technology Ready	Shuttle Flight	EOS Flight*	Measurement	Candidate Lasers
I.	1987 ± 1	1990 ± 1	1993 ± 1	Aerosol/cloud distribution and planetary boundary layer (1λ)	Many choices (0.5-1.0 μm)
				Coarse aerosol distribution and tropopause height (3λ)	Nd:YAG (0.35, 0.53, and 1.06 μm)
				H_2O - CC and RR (Δz = 2 km, mid-to-low troposphere)	Alexandrite
				O_3 - CC and RR (Δz = 2 km)	Excimer (Raman-shifted)
II.	1992	1995	1997	H_2O (Δz = 1 km through troposphere)	Nd:GLASS (Raman-shifted)
				NH_3 - CC	CO_2
				Temperature (Δz = 1 km)	Alexandrite
III.	2000	2005	2010	NO_2 - CC	Excimer (Raman-shifted)
				SO_2 - CC	Excimer (Raman-shifted)
				NO - CC	Not identified
				CH_4 - CC and RR	Not identified
				CO - CC and RR	Not identified
				H_2O_2 - CC	Not identified

* Lidar operated at 10 percent duty cycle, Period I.

CC ≡ Column content

RR ≡ Range resolved (profiles)

nλ ≡ n number of lidar wavelengths

Δz ≡ vertical resolution of lidar measurement

TABLE IX.- ASSESSMENT OF LASER AVAILABILITY FOR SPACE MISSIONS

Species	Laser	Time Frame: Shuttle*	Time Frame: EOS (10% Duty)	Time Frame: Long Life EOS
H_2O	Alexandrite	I	I**	II
	CO_2 (CW)	I+	I+	II-III
	Ti:Al_2O_3	II	II	III
	Nd:YAG-Dye	II	II	III
	Nd:GLASS	II	II	III
	OPO	II	II	III
O_3	Excimer	I	I	II
	CO_2	II	II	II
CO	2X-CO_2	III	III	III
CH_4	?	III	III	III
NH_3	CO_2	II	II	II
Aerosols	Nd:YAG (2X; 3X)	I	I	I-II
	Excimer + Raman	I	I	II
	Alexandrite	I	I	II
	Ti:Al_2O_3	II	II-III	II-III
	Diode-pumped YAG	II	II-III	II-III
NO	2X-CO_2	III	III	III
NO_2	Excimer + Raman	II	III	III
SO_2	Excimer + Raman	II	III	III
H_2O_2	?	III	III	III

*Shuttle: I--1990; II--1995; III--2005
EOS: I--1993; II--1997; III--2010
**Category I for H_2O column content and lower trop. H_2O profiles (mostly at night)
Category II for lower and upper trop. H_2O profiles day/night
+Column content only
2X ≡ frequency doubled laser output
3X ≡ frequency tripled laser output

WORKSHEETS ON LIDAR TECHNOLOGY

This section presents the worksheets produced by the Lidar Measurements and Technology Working Group. They essentially list the most pressing technical issues for the laser remote sensing of each identified atmospheric constituent from space.

LASER REMOTE SENSING WORKSHEET

SPECIES: **Aerosols**

1. Wavelength: 1.06 μm
   0.53 μm
   0.355 μm

2. Adequate Optical Depth: N/A

3. Any Unique Spectra Requirements: None

4. Appropriate Laser Source: Nd:YAG + 2X, 3X

TECHNICAL ISSUES:

- Well demonstrated
- Probable lifetime, efficiency?
- Detect at 1.06 μm--limited availability of PMT
- Size distribution from 3 λ values

5. Estimate of Appropriate Field Demonstration:
   - Airborne demonstration completed
   - LITE (Shuttle) 1989

6. Estimate of Measurement Resolution (Accuracy):
   - 1 λ → 50 percent error
   - 3 λ → 10 percent error

LASER REMOTE SENSING WORKSHEET

SPECIES: **Aerosols**

1. Wavelength:
   - 0.3 μm
   - 10.6 μm

2. Adequate Optical Depth:
   - Okay at 0.3 μm
   - Little backscatter at 10.6 μm

3. Any Unique Spectra Requirements: None

4. Appropriate Laser Source:
   - Excimer (0.3 μm)
   - CO_2 (10.6 μm)

TECHNICAL ISSUES:

Excimer

- Raman shift to 0.35, 0.5, and 0.6 μm

CO_2

- Need heterodyne detection
- Outgrowth of Doppler lidar
- More complex than 1 μm
- If air is clean, then no signal

5. Estimate of Appropriate Field Demonstration:
   - Excimer--Need airborne demonstration
   - CO_2--Labratory demonstration complete

6. Estimate of Measurement Resolution (Accuracy): TBD

LASER REMOTE SENSING WORKSHEET

SPECIES: **Aerosols**

1. Wavelength: 0.7 μm
   0.5 μm

2. Adequate Optical Depth: N/A

3. Any Unique Spectra Requirements: None

4. Appropriate Laser Source:
   - Alexandrite (0.7 μm)
   - Ti:Sapphire (0.7 μm)
   - Diode Pumped (0.5 μm) Nd:YAG (2X, 3X)

TECHNICAL ISSUES:

Alexandrite	Ti:Sapphire	Diode Pumped
• Energy Okay (1/2 joule) • Lifetime? • Efficiency? • Possibility of Doppler/aerosol spectral resolution	• 2-5 years development needed	• 2-5 years development required

5. Estimate of Appropriate Field Demonstration: 1988

6. Estimate of Measurement Resolution (Accuracy): TBD

LASER REMOTE SENSING WORKSHEET

SPECIES: H_2O

1. Wavelength: 0.72 μm

2. Adequate Optical Depth: Okay

3. Any Unique Spectra Requirements: $\Delta\lambda$ = 1 pm lower troposphere spectral purity >99 percent

4. Appropriate Laser Source:
   - YAG Pumped Dye
   - Alexandrite
   - $Ti:Al_2P_3$

TECHNICAL ISSUES:

YAG Pumped Dye

- Current status power x 5 too low
- Spectral purity problem
- Large size
- Lifetime: 10^5-10^6 shots

Alexandrite

- Power okay for CC
- Power low (X3 for range resolved
- Low efficiency
- Lifetime?
- P ≈ 1/2 joule in 2 years

$TI:Al_2O_3$

- Low proven power
- Need demonstration tuning and linewidth

Need wavemeter development

5. Estimate of Appropriate Field Demonstration: 1988--Alexandrite DIAL system with wavemeter demonstrated in ER-2

6. Estimate of Measurement Resolution (Accuracy): 5 percent CC
   10 percent ΔR

LASER REMOTE SENSING WORKSHEET

SPECIES: H_2O

1. Wavelength: 0.94 μm

2. Adequate Optical Depth: Okay

3. Any Unique Spectra Requirements: 0.5 picometer linewidth for upper troposphere

4. Appropriate Laser Source:
   - Dye
   - Nd:GLASS
   - $Ti:Al_2O_3$ and OPO

TECHNICAL ISSUES:

Dye	Nd:GLASS	$Ti:Al_2O_3$ and OPO
• Low power	• Raman shift • Emerging technology: slabs (2-5 years)	• Requires development • Raman shift

Detectors: Avalanche photodiode?

5. Estimate of Appropriate Field Demonstration: ≈1988 for Dye and Nd:GLASS DIAL measurements

6. Estimate of Measurement Resolution (Accuracy): Aerosol backscatter same as 0.72 μm H_2O

LASER REMOTE SENSING WORKSHEET

SPECIES: H_2O

1. Wavelength: 10.6 μm

2. Adequate Optical Depth: Optical depth?

3. Any Unique Spectra Requirements: TBD

4. Appropriate Laser Source: CO_2

TECHNICAL ISSUES:

- Heterodyne detector required
- (Okay for CW--Column content)
- Use Homodyne

5. Estimate of Appropriate Field Demonstration: TBD

6. Estimate of Measurement Resolution (Accuracy): TBD

LASER REMOTE SENSING WORKSHEET

SPECIES: O_3

1. Wavelength: 0.308 μm

2. Adequate Optical Depth: Okay

3. Any Unique Spectra Requirements: No frequency control; O_3 band is broad

4. Appropriate Laser Source: Excimer (Need ≈4Å filter for detection)

TECHNICAL ISSUES:

- Raman shift for off-line
- Current powers okay
- Lifetime?
- Penetration through stratosphere?
- Good atmospheric backscatter at 3080 Å

5. Estimate of Appropriate Field Demonstration: Need balloon tests

6. Estimate of Measurement Resolution (Accuracy): TBD

LASER REMOTE SENSING WORKSHEET

SPECIES: O_3

1. Wavelength: 10 μm

2. Adequate Optical Depth: Okay

3. Any Unique Spectra Requirements: Single Frequency

4. Appropriate Laser Source: CO_2

TECHNICAL ISSUES:

Pulsed CO_2

- Okay for column content
- Possible lifetime problem
- Differential albedo problem
- Penetration through stratospheric O_3? (Tune to side of line.)

CW CO_2

- Column content
- No lifetime problem

5. Estimate of Appropriate Field Demonstration: Need balloon tests (35-40 km)

6. Estimate of Measurement Resolution (Accuracy): 10 percent?

LASER REMOTE SENSING WORKSHEET

SPECIES: NH_3

1. Wavelength: 10μm

2. Adequate Optical Depth: TBD

3. Any Unique Spectra Requirements: May be problem due to small optical depth and shallow layer

4. Appropriate Laser Source: CO_2

TECHNICAL ISSUES:

- Heterodyne detection
- Same status as CO_2 DIAL for O_3 (except no stratospheric burn through problem as with ozone)

5. Estimate of Appropriate Field Demonstration: TBD

6. Estimate of Measurement Resolution (Accuracy): TBD

LASER REMOTE SENSING WORKSHEET

SPECIES: CH_4

1. Wavelength: 7.7 μm
   3.3 μm

2. Adequate Optical Depth: TBD

3. Any Unique Spectra Requirements: TBD

4. Appropriate Laser Source: No current lasers

   TECHNICAL ISSUES:

   Future Candidate Lasers:

   a. Raman shift Alexandrite
   b. Solid-state tunable laser

5. Estimate of Appropriate Field Demonstration: TBD

6. Estimate of Measurement Resolution (Accuracy): TBD

LASER REMOTE SENSING WORKSHEET

SPECIES: CO

1. Wavelength: 4.6 μm
2.3 μm

2. Adequate Optical Depth: Okay

3. Any Unique Spectra Requirements: TBD

4. Appropriate Laser Source: Doubled CO_2 or CO at 4.6 μm

TECHNICAL ISSUES:

Current Lasers Lack Power at 4.6 μm

- 2X CO_2--Need hèterodyne detector (L. O. problem)
- Possible CO laser (optical depth?)

No Current Laser at 2.3 μm

Future: Raman shift (5 Years?)

5. Estimate of Appropriate Field Demonstration: TBD

6. Estimate of Measurement Resolution (Accuracy): TBD