ADVANCED AIRBORNE DIAL SYSTEMS, THEIR MEASUREMENTS, AND PLANS FOR FUTURE SPACEBORNE DIAL MISSIONS

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ABSTRACT

Major advances have taken place in recent years in the development and application of airborne Differential Absorption Lidar (DIAL) systems in the measurement of water vapor (H_2O), ozone (O_3), and aerosols in various regions of the atmosphere. This paper describes advanced airborne DIAL systems for measurements of H_2O, aerosols, and clouds; and of O_3 and aerosols. It also presents results from recent field experiments using these systems. Future spaceborne DIAL investigations in these areas are also discussed.

DIAL SYSTEMS FOR WATER VAPOR, AEROSOLS, AND CLOUDS

Recent atmospheric measurements of H_2O and aerosol distributions have been made with two different DIAL systems operating on two aircraft. One DIAL system uses an alexandrite laser and operates from a medium-altitude aircraft (e.g., Electra or DC-8) and the other is an autonomous DIAL system called LASE (Lidar Atmospheric Sensing Experiment) that uses a Ti:sapphire laser and operates from a high-altitude aircraft (ER-2). In the following sections, each of these systems are described, and a future spaceborne DIAL mission for H_2O, aerosol, and clouds measurements is discussed.

Alexandrite DIAL System

The NASA Langley Research Center's (LaRC) airborne H_2O DIAL system uses a narrowband, tunable alexandrite laser as the on-line transmitter and an Nd:YAG-laser-pumped dye laser as the off-line transmitter [Higdon et al., 1994]. Both of these lasers are operated in conjunction with a H_2O absorption line in the 727-nm region. The alexandrite laser uses three intracavity tuning elements to produce an output linewidth of $\leq$1.1 pm. The tuning elements include a five-plate birefringent tuner, a 1-mm-thick solid etalon, and a 1-cm air-spaced etalon. A wavelength stability of ±0.35 pm is achieved by active feedback control of two Fabry-Perot etalons using a frequency stabilized He-Ne laser as a wavelength reference. The three tuning elements are synchronously scanned over a 150-pm range with microprocessor-based scanning electronics. Details of the DIAL transmitter, receiver, and data systems are given by Higdon et al. [1994]. During the past year, the dye laser was replaced with a second alexandrite laser and the linear cavity design of the on-line laser was changed to a ring configuration. Also diode injection seeding of the on-line laser is now being used for locking to the H_2O absorption line.

The first extensive observations of H_2O and aerosols in the lower troposphere were made with the airborne DIAL system during the spring of 1990 and the summer of 1991. Water vapor measurements were made on flights at night over the ocean, during the day over land and ocean, and across a cold front. Daytime H_2O distributions obtained by the airborne DIAL system as the aircraft crossed over the coast of Virginia clearly showed the decrease in the mixed layer depth from about 1.7 km over land to less than 1 km over the water. The boundary layer was moist with dry atmospheric conditions aloft. Regions with enhanced H_2O concentrations were correlated with higher aerosol backscattering in the lidar data. The airborne DIAL measurements showed for the first time the detailed H_2O and aerosol structure that occurs in the free troposphere and in the mixed layer over different land and marine regimes.

LASE

The LASE system is the first fully autonomous DIAL system and a precursor to a spaceborne DIAL system. LASE uses a double-pulse Ti:sapphire laser for the generation of the on- and off-line DIAL wavelengths in the 820-nm band of H_2O. The Ti:sapphire laser is pumped by a double-pulsed, frequency-doubled Nd:YAG laser, and the spectral output of the Ti:sapphire laser is controlled by an injection-seeded semiconductor diode laser. The wavelength of the diode laser is locked to a H_2O line using a frequency modulation technique that uses a H_2O absorption cell. The on- and off-line laser pulses are transmitted with 400 μs separation, and these pulse pairs are transmitted below the ER-2 at 5 Hz. The laser energy is 140 mJ, and the laser linewidth is less than 0.35 pm. LASE can be operated on two different H_2O lines during a flight. The receiver system consists of a 38-cm diameter telescope with an adjustable field of view. A 300 pm bandpass filter is used to minimize background noise during daytime operation. Two avalanche photodiodes (APD's) are used for the lidar signal detection (one for a high-gain channel and the other for a low-gain channel). The signals from the APD's are digitized at 5 MHz with a 12-bit A/D. The data are stored on a hard disk and also telemetered back to the LASE ground station for real-time analysis.

The first LASE measurements of H_2O, aerosols, and clouds were made from the NASA ER-2 aircraft on a flight near the NASA Wallops Flight Facility in the early morning hours of September 17, 1994. The LASE measurements showed the distribution of H_2O and aerosols along the ground track of the ER-2, which was flying at an altitude of 20 km. The aerosol distribution showed the high concentration of aerosols near the surface (below 4 km), and the presence of high-altitude cirrus clouds in the altitude range from 8 to 10 km. The H_2O distribution measured by LASE showed the very humid conditions at low altitudes and generally dry regions above 3 km. There was an enhancement of moisture observed in the altitude region associated with the cirrus clouds. The tropopause was at about 10 km, and the LASE measurements show very low H_2O (<0.01 g/kg) in the lower stratosphere.

In September 1995, LASE completed a comprehensive validation program at the NASA Wallops Flight Facility. The system was flown on the ER-2 during ten flights for a total of 60 hours. LASE measurements of tropospheric H_2O were compared with other remote and in situ measurements of H_2O from the ground and from aircraft which were flown under the ER-2. A NASA Lear Jet carried a Buck CR-1 and a GE 1011 in situ sampling hygrometers; and a NASA C-130 was equipped with the NASA LaRC airborne DIAL system and a GE 1011 hygrometer for additional remote and in situ H_2O measurements. A number of radiosondes were launched coincident with the ER-2 flights and many of these sondes were part of a World Meteorological Organization balloon campaign. The NASA Goddard Flight Center Raman lidar provided remote measurements from the ground. Besides making intercomparisons with a number of H_2O sensors, this experiment incorporated a number of case studies related to atmospheric events including flights over and around Hurricane Luis over the Atlantic ocean, sea breeze development, and strat-trop exchange.

Spaceborne Water Vapor DIAL Mission

A future spaceborne DIAL system for the measurement of global distributions of H_2O, aerosols, and clouds is being studied by the NASA LaRC. This system would address key environmental issues related to climate, radiation budgets, weather, and atmospheric chemistry. Measurements of H_2O profiles with a vertical resolution of 0.5 to 1.0 km and a horizontal resolution of 100 km with better than 10% accuracy appears to be possible from a small satellite in low-Earth orbit. At least two H_2O absorption lines will be used nearly simultaneously to cover all of the troposphere below about 10 km.

Simultaneous measurements of aerosol and cloud distributions will also be made with 50- to 100-m vertical resolution and 1-km horizontal resolution.

DIAL SYSTEMS FOR OZONE AND AEROSOLS

Airborne Ozone DIAL System

The NASA LaRC airborne O_3 DIAL system uses two frequency-doubled Nd:YAG lasers to pump two high-conversion-efficiency, frequency-doubled, tunable dye lasers. The four lasers are mounted on a structure that supports all of the laser power supplies, the laser beam transmitting optics, and the dual telescope and detector packages for simultaneous nadir and zenith measurements. In tropospheric O_3 investigations, one of the frequency-doubled dye lasers is operated at 289 nm for the DIAL on-line wavelength, and the other one is operated at 300 nm for the off-line wavelength. The DIAL wavelengths are produced in sequential laser pulses with a time separation of ~300 µs. For tropospheric investigations, half of each ultraviolet beam is transmitted in the zenith and nadir directions. The residual dye laser output at 600 and 582 nm that is left after the frequency-doubling process and the residual 1064-nm output from the frequency-doubled Nd:YAG laser are also transmitted for aerosol profile measurements. The output beams are transmitted out of the aircraft coaxially with the receiver telescopes through 40-cm-diameter quartz windows. In stratospheric investigations, the on- and off-line wavelengths are 301 and 311 nm, respectively, and all the ultraviolet beams are transmitted in the zenith direction. Detailed characteristics of the current airborne DIAL system and the O_3 DIAL technique are given by Browell [1989; 1995].

Large-scale O_3 and aerosol distributions were recently investigated with the airborne DIAL system in the troposphere over the western Pacific in the PEM-West (Pacific Exploratory Mission - West) field experiment [Browell et al., 1995] and the tropical Atlantic during the TRACE-A (Transport and Atmospheric Chemistry near the Equator--Atlantic) field experiment [Browell et al., 1996]. Airborne DIAL measurements in the lower stratosphere were made in the Arctic during the 1989 and 1992 Airborne Arctic Stratospheric Expeditions (AASE-I & II) [Browell et al., 1990; 1993].

Spaceborne Ozone DIAL System

NASA and the Canadian Space Agency (CSA) are jointly studying the development of a spaceborne lidar system for global measurements of O_3 and aerosol distributions in the troposphere and lower stratosphere. This lidar system called ORACLE (Ozone Research with Advanced Cooperative Lidar Experiments) will be capable of measurements of O_3 profiles and columns across the lower atmosphere with simultaneous measurements of aerosol and cloud profiles. This advanced lidar system will provide global tropospheric O_3 profile measurements not possible by any other currently available sensor, and it will complement and enhance the capability of satellite-based passive remote sensing systems in the stratosphere. The O_3 and aerosol measurements obtained by the ORACLE system will provide key information needed for assessing global environmental issues related to global change, atmospheric chemistry, O_3 depletion, climate, atmospheric dynamics, and meteorology.

An estimate of ORACLE's transmitter and receiver characteristics have been made, and these parameters have been used to provide an initial assessment of the measurement capability of ORACLE under a wide range of atmospheric and solar background conditions. It is estimated that ORACLE would be able to measure tropospheric O_3 with an accuracy of 10% or 5 ppbv, whichever is greater, with a vertical resolution of $\leq$2.5 km and a horizontal resolution of about 250 km. The vertical resolution in the lower stratosphere can be less than 1 km with a horizontal resolution of 100 km. Simultaneous aerosol and cloud measurements can be made with high vertical (<100 m) and horizontal (<1 km) resolutions, and these aerosol data can be used to focus the O_3 measurements across the boundary layer and across layers in the free troposphere and lower stratosphere. These measurements are of particular importance to atmospheric process studies related to the influence of aerosol and clouds on the chemistry and transport of O_3 in the atmosphere.

CONCLUSIONS

Many important atmospheric studies of H_2O, O_3, aerosols, and clouds have been conducted with airborne DIAL systems. These applications have demonstrated the maturity of the field and the value of these remote measurements to atmospheric investigations. Advanced airborne DIAL systems have also demonstrated the technology and techniques that are needed for the development of a spaceborne DIAL system. Atmospheric science missions and requirements for future spaceborne DIAL systems have been defined, and studies are underway that would lead to the development of a small-satellite-based DIAL system for the measurement of H_2O, aerosols, and clouds or O_3 and aerosols.

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Higdon, N. S., et al., Airborne differential absorption lidar system for measurements of atmospheric water vapor and aerosols, Appl. Opt., 33, 6422-6438, 1994.

Advanced Airborne DIAL Systems and Measurements and Plans for Future Spaceborne DIAL Missions

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ATMOSPHERIC SCIENCE MEASUREMENT NEEDS

PARAMETER	RATIONALE
● OZONE	● IMPORTANT STRATOSPHERIC SPECIES FOR UV ABSORPTION OF SOLAR RAD.
	● IMPORTANT RADIATIVE GAS IN TROP. THAT CAN EFFECT CLIMATE WARMING TRENDS
	● IMPORTANT OXIDIZING AGENT IN TROP. THAT PRODUCES OH
● WATER VAPOR	● MOST IMPORTANT RADIATIVE GAS IN TROPOSPHERE
	● SENSITIVE FEEDBACK FOR CLIMATE WARMING
	● IMPORTANT IN CLOUD FORMATION FEEDBACK TO CLIMATE WARMING
	● SOURCE OF OH IN TROP. WHICH CONTROLS TROP. CHEMISTRY

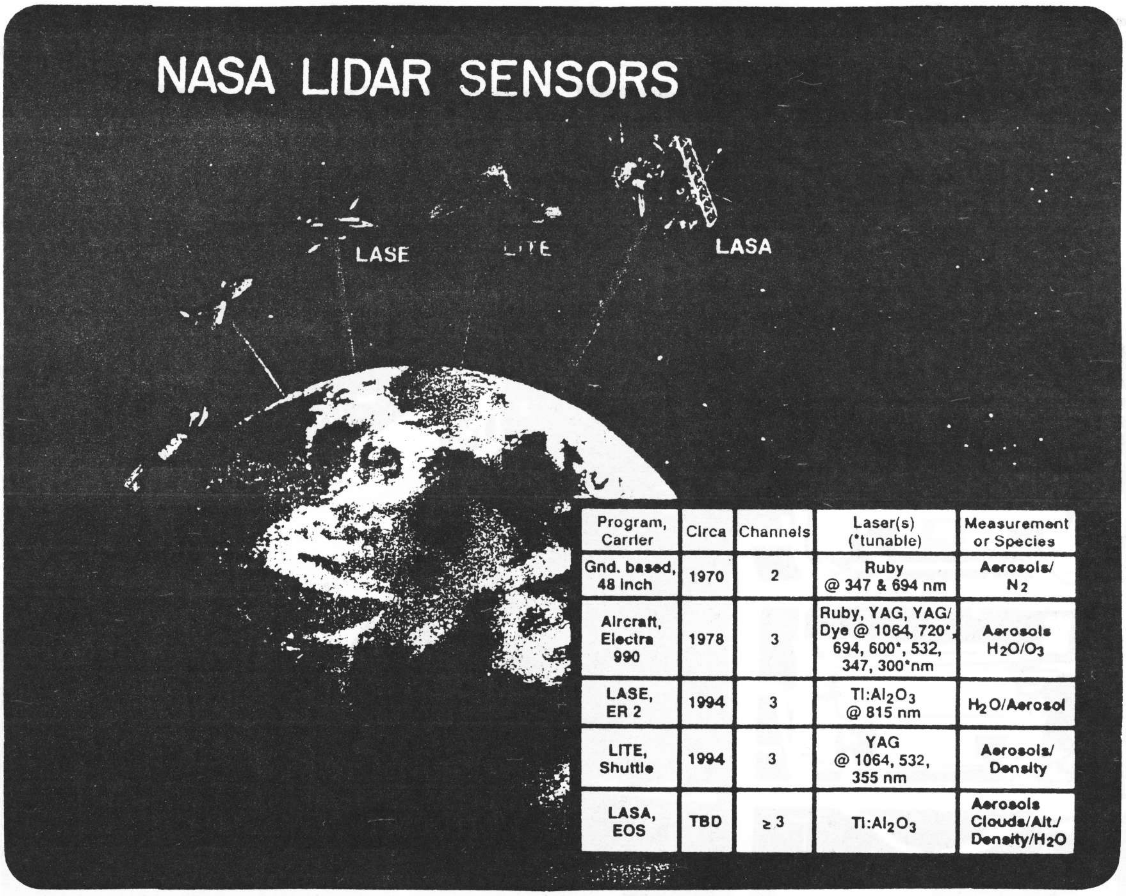
ATMOSPHERIC SCIENCE MEA. NEEDS CON'T

PARAMETER	RATIONALE
● AEROSOLS/CLOUDS	● IMPORTANT RADIATIVE COMPONENTS THAT STRONGLY INFLUENCE CLIMATE MODELS
	● IMPORTANT INFLUENCE IN DRIVING ATMOSPHERIC MOTIONS AND ENERGY DISTRIBUTION
	● IMPORTANT ROLE IN BIOGEOCHEMICAL CYCLES & ATMOSPHERIC CHEMISTRY

Spectral Regions for Lidar Measurements

Measurement	Lidar Wavelengths
● Trop. Ozone (DIAL)	● 289 (λ_{on}) & 300 nm (λ_{off})*
● Strat. Ozone (DIAL)	● 301 (λ_{on}) & 311 nm (λ_{off})
● Trop. Water Vapor (DIAL)	● 727, 820, or 940 nm region for λ_{on} & λ_{off} ($\Delta\lambda<0.1$ nm)
● Aerosol Backscattering	● 300, 600, & 1064 nm
● Aerosol Depolarization	● 600 & 1064 nm

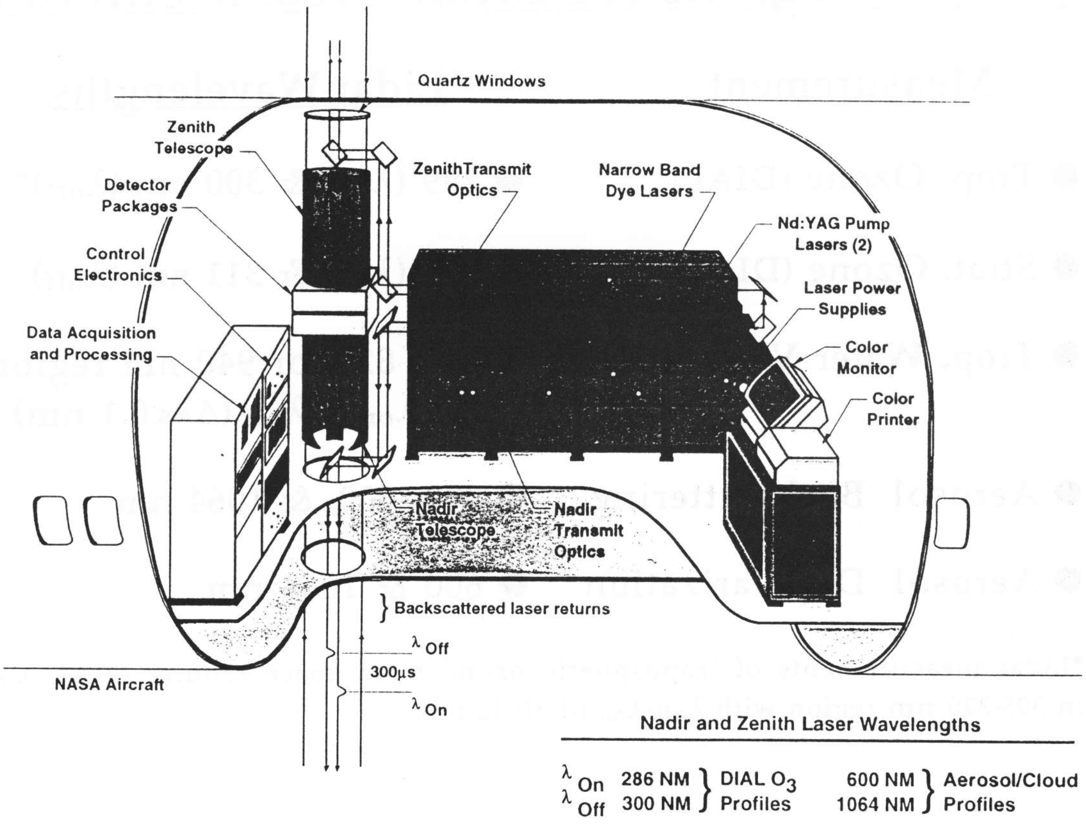
*Lidar measurements of tropospheric ozone from space require DIAL λ's in 305-320 nm region with λ_{off}-λ_{on} of 10-12 nm.



NASA LIDAR SENSORS

Program, Carrier	Circa	Channels	Laser(s) (*tunable)	Measurement or Species
Gnd. based, 48 inch	1970	2	Ruby @ 347 & 694 nm	Aerosols/ N_2
Aircraft, Electra 990	1978	3	Ruby, YAG, YAG/ Dye @ 1064, 720*, 694, 600*, 532, 347, 300*nm	Aerosols H_2O/O_3
LASE, ER 2	1994	3	$Ti:Al_2O_3$ @ 815 nm	H_2O/Aerosol
LITE, Shuttle	1994	3	YAG @ 1064, 532, 355 nm	Aerosols/ Density
LASA, EOS	TBD	≥ 3	$Ti:Al_2O_3$	Aerosols Clouds/Alt./ Density/H_2O

Airborne DIAL System Configuration



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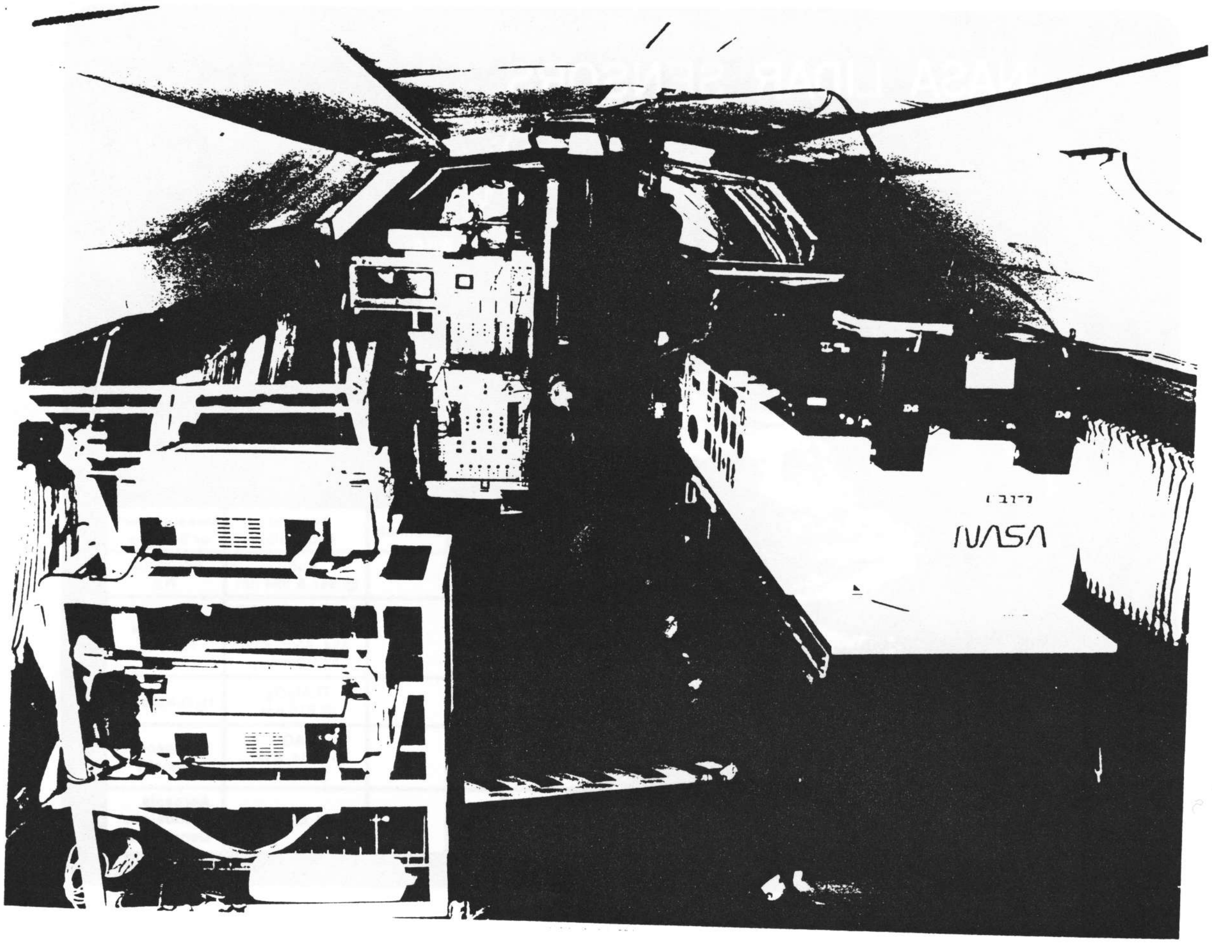
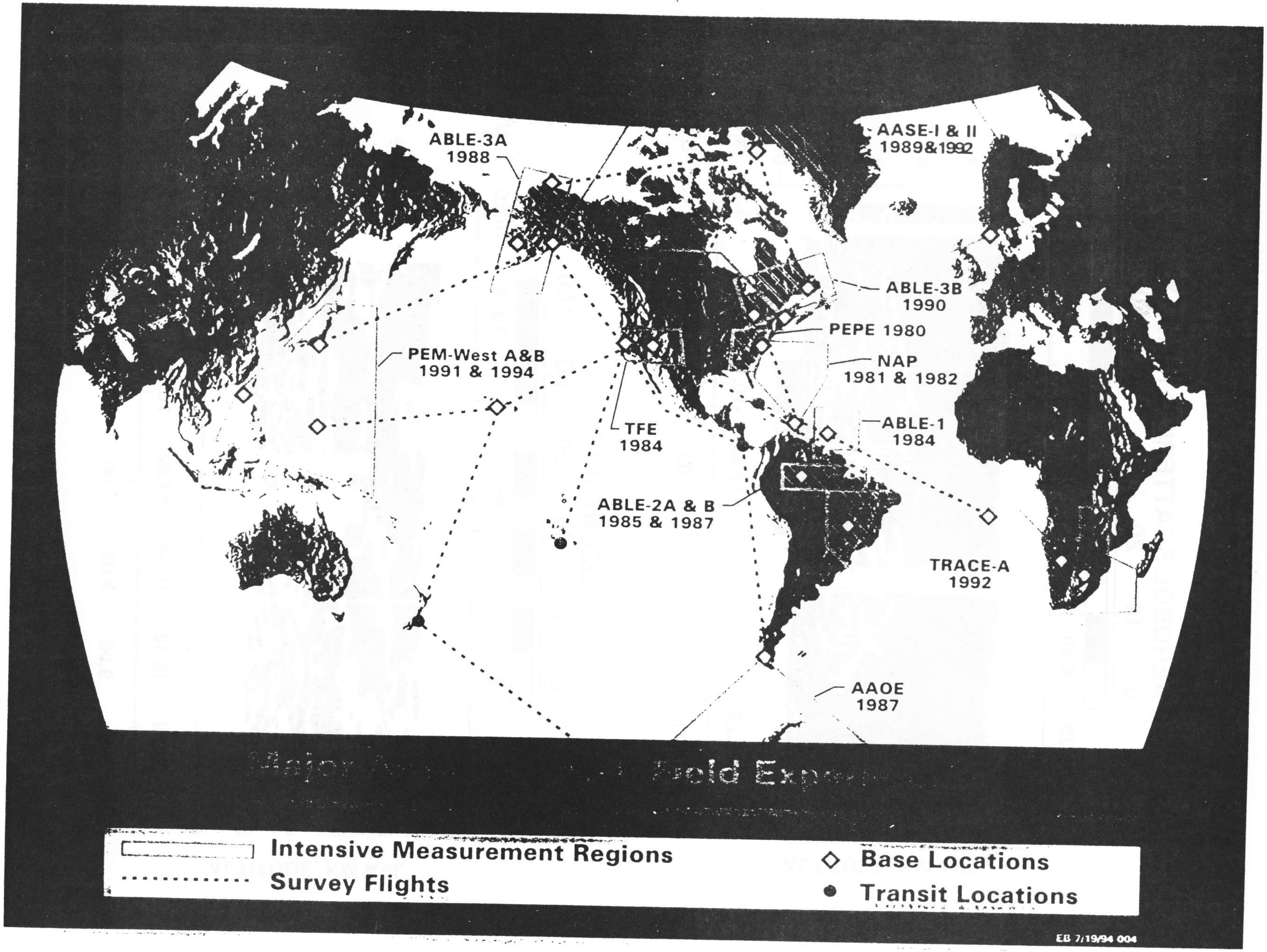
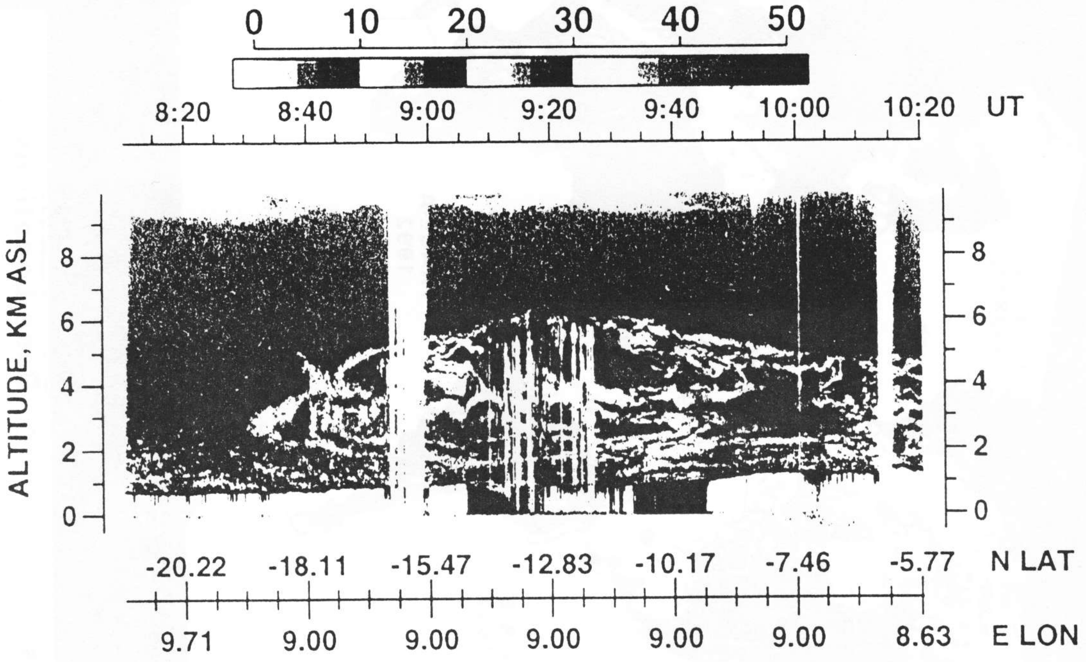


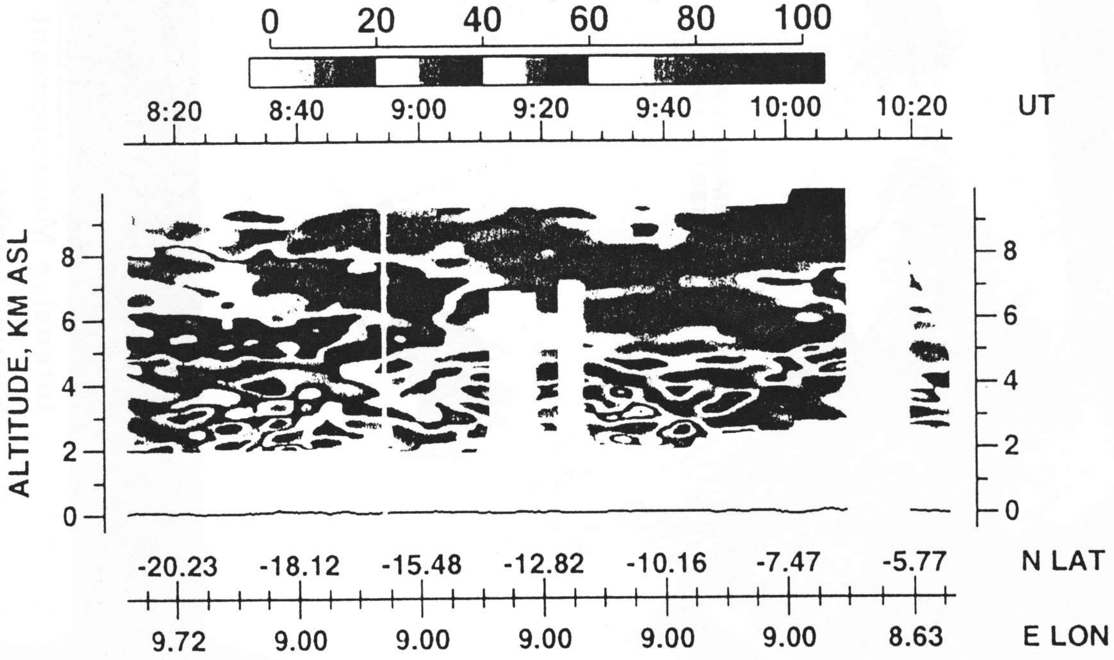

ABLE-3A
1988
AASE-I & II
1989&1992
ABLE-3B
1990
PEPE 1980
NAP
1981 & 1982
PEM-West A&B
1991 & 1994
TFE
1984
ABLE-1
1984
ABLE-2A & B
1985 & 1987
TRACE-A
1992
AAOE
1987
Major
Field Exp
Intensive Measurement Regions
Survey Flights
◇ Base Locations
● Transit Locations
EB 7/19/94 004

AFRICAN OUTFLOW - WEST (DAY 1)

TRACE-A FLIGHT 13 14 OCT 92



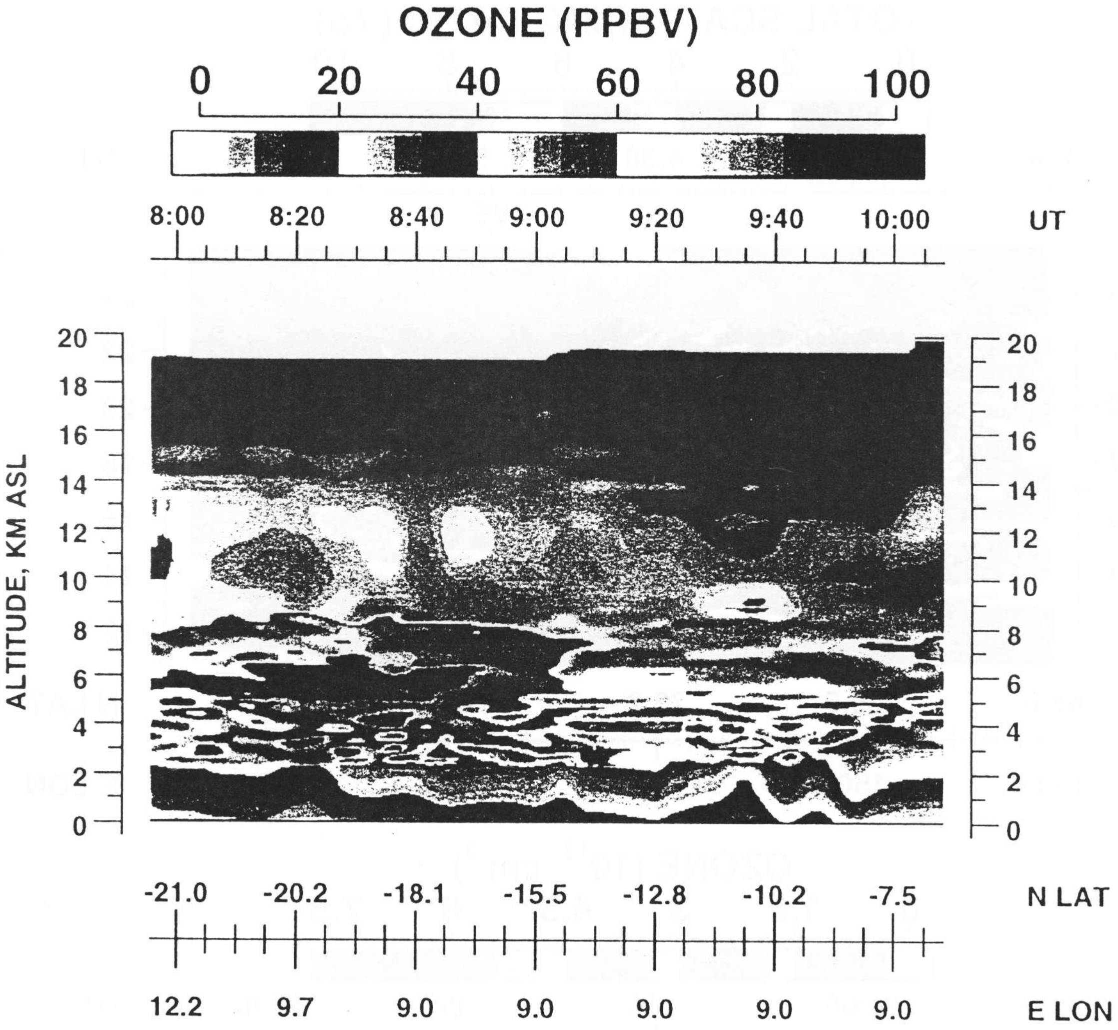
RELATIVE AEROSOL SCATTERING RATIO X 1000 (IR)



OZONE (PPBV)

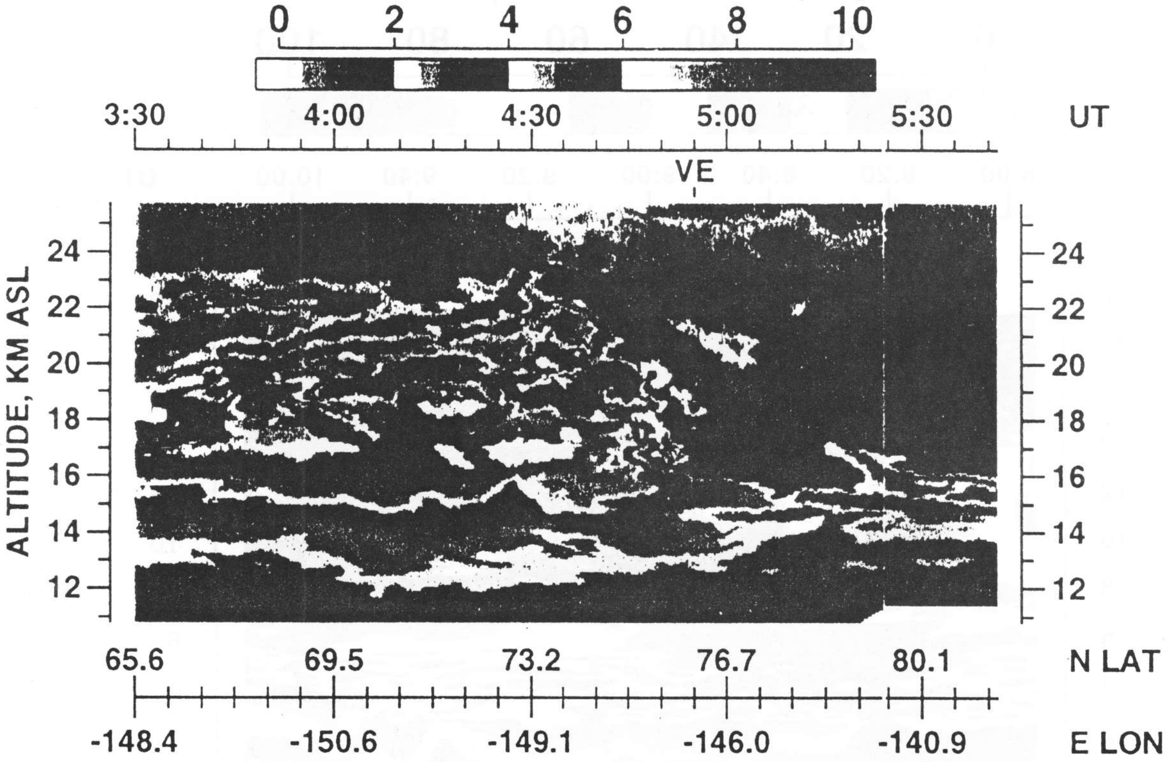
AFRICAN OUTFLOW - WEST (DAY 1)

TRACE-A **FLIGHT 13** **14 OCT 92**

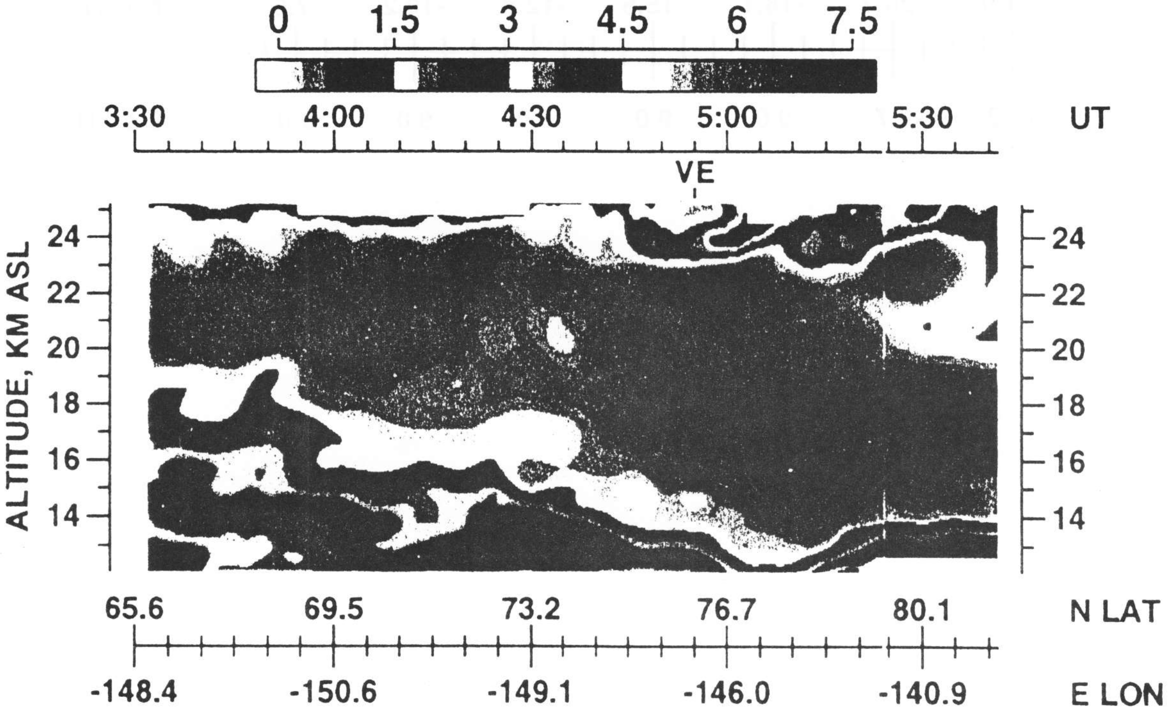


ALASKA TO NORWAY

AASE II **FLIGHT 4** **16 JAN 92**

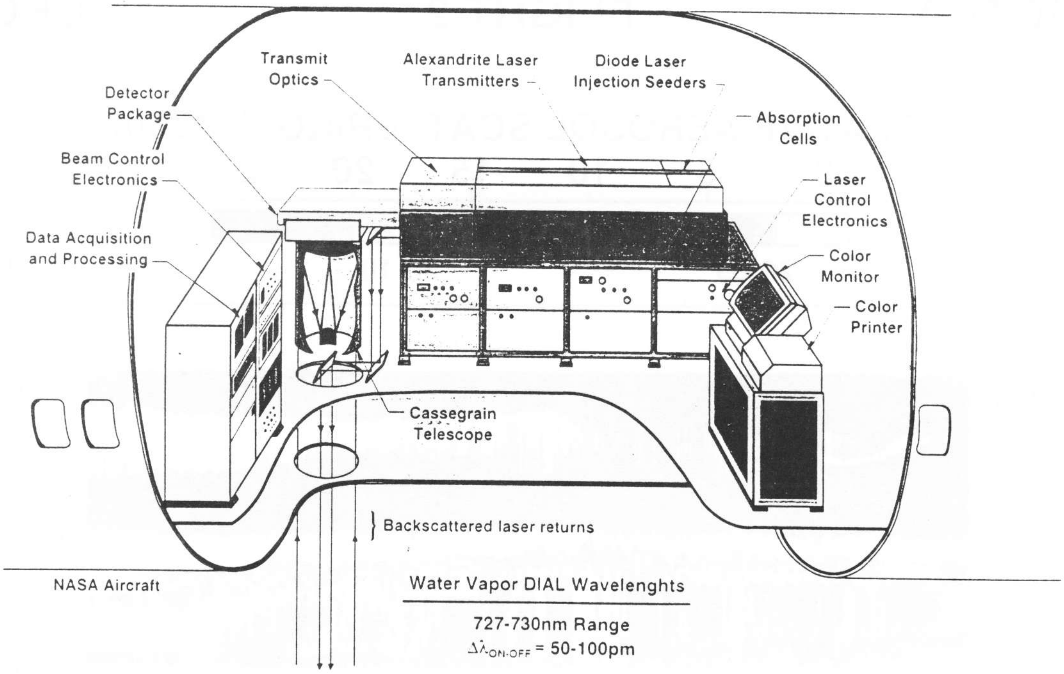


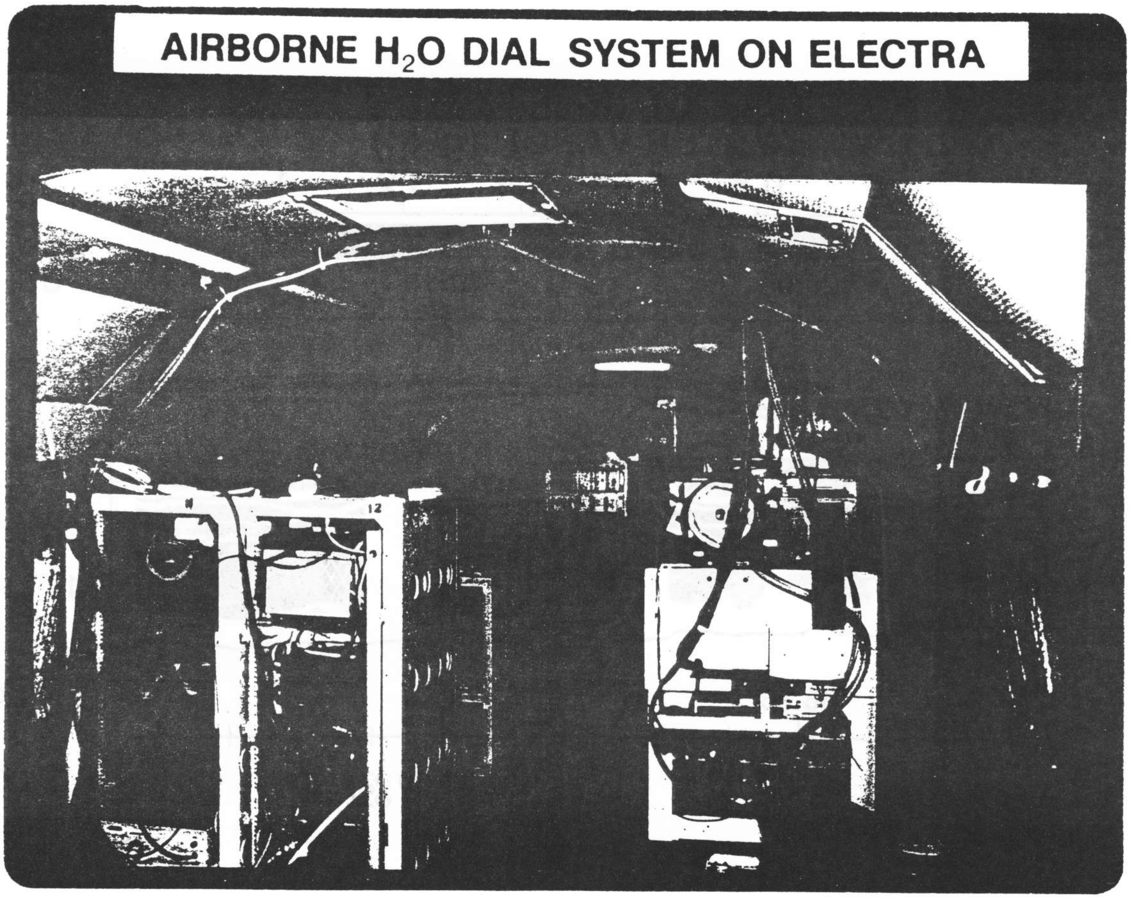
TOTAL SCATTERING RATIO (VS)



OZONE (10^{12} cm^{-3})

Airborne Water Vapor DIAL System Configuration

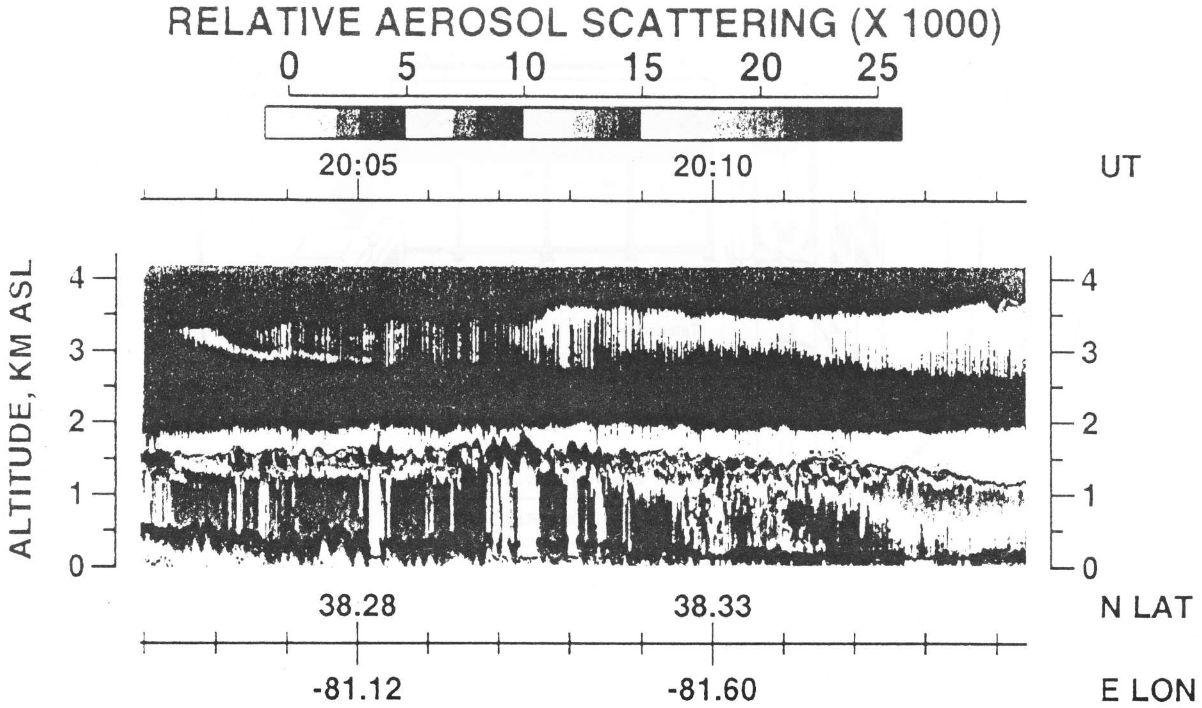


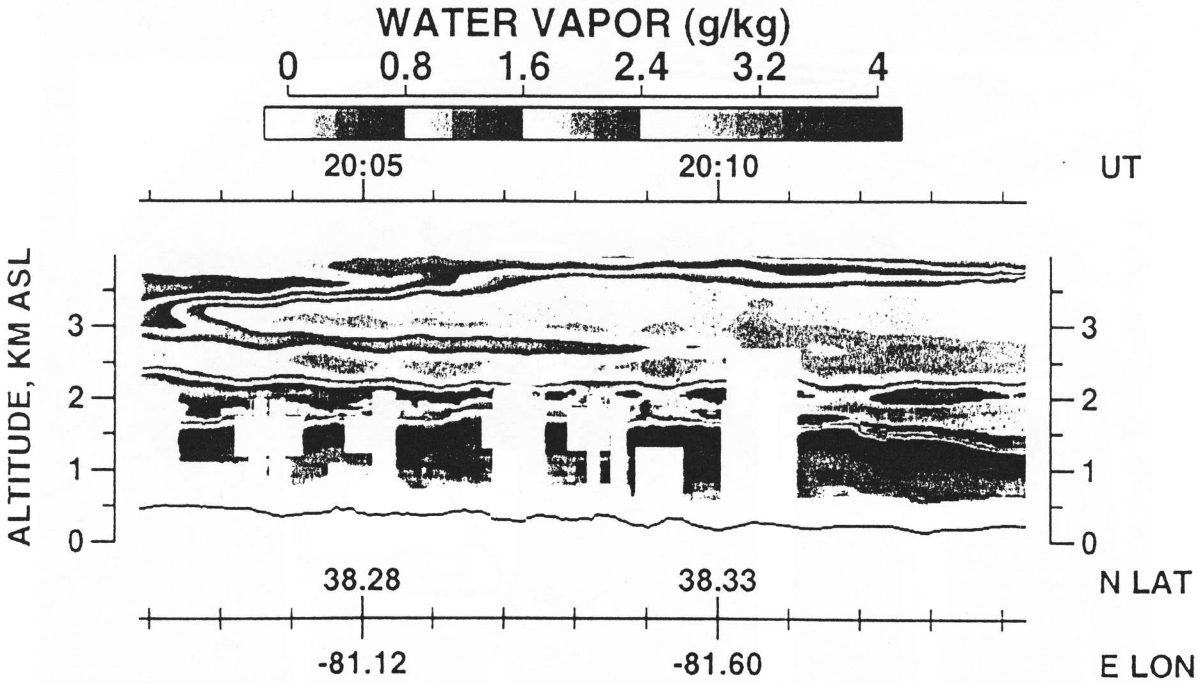


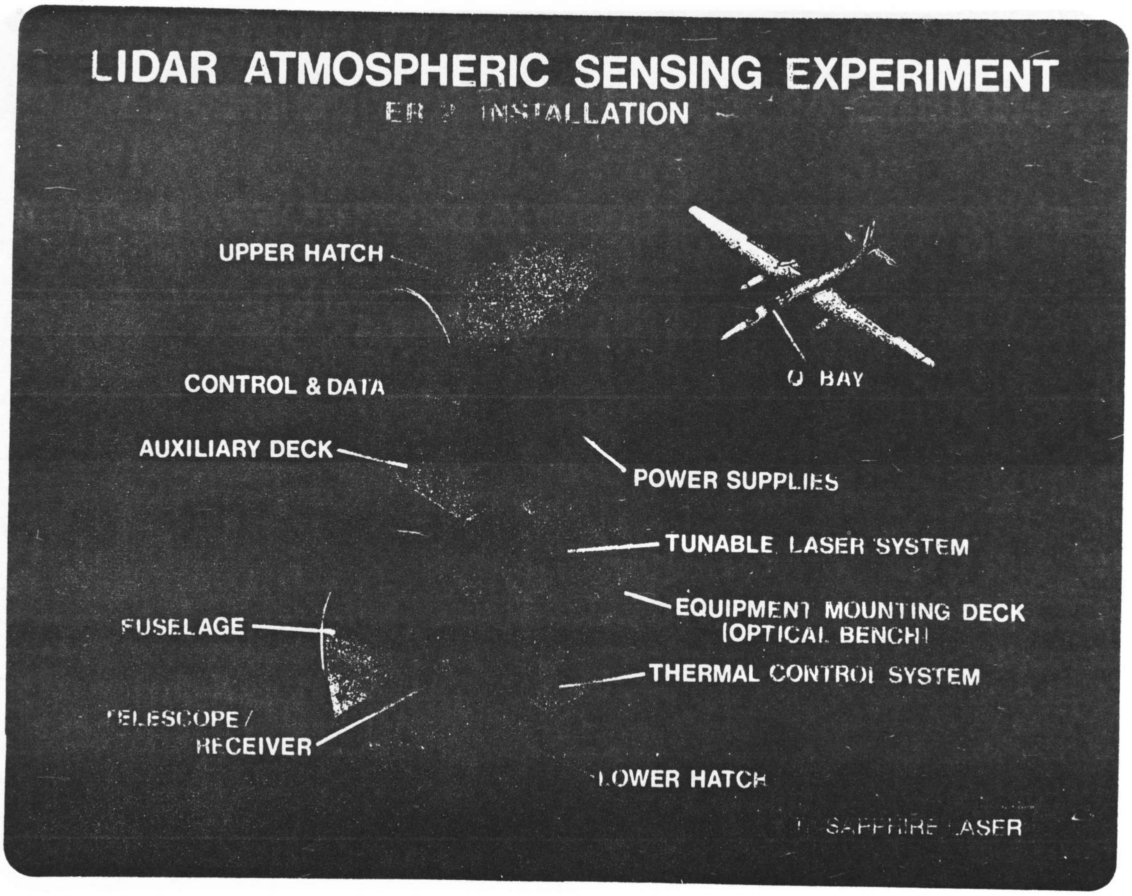
AIRBORNE H_2O DIAL SYSTEM ON ELECTRA

HUNTINGTON, WV

ELECTRA **FLIGHT 2** **15 DEC 94**







LASE SYSTEM BLOCK DIAGRAM

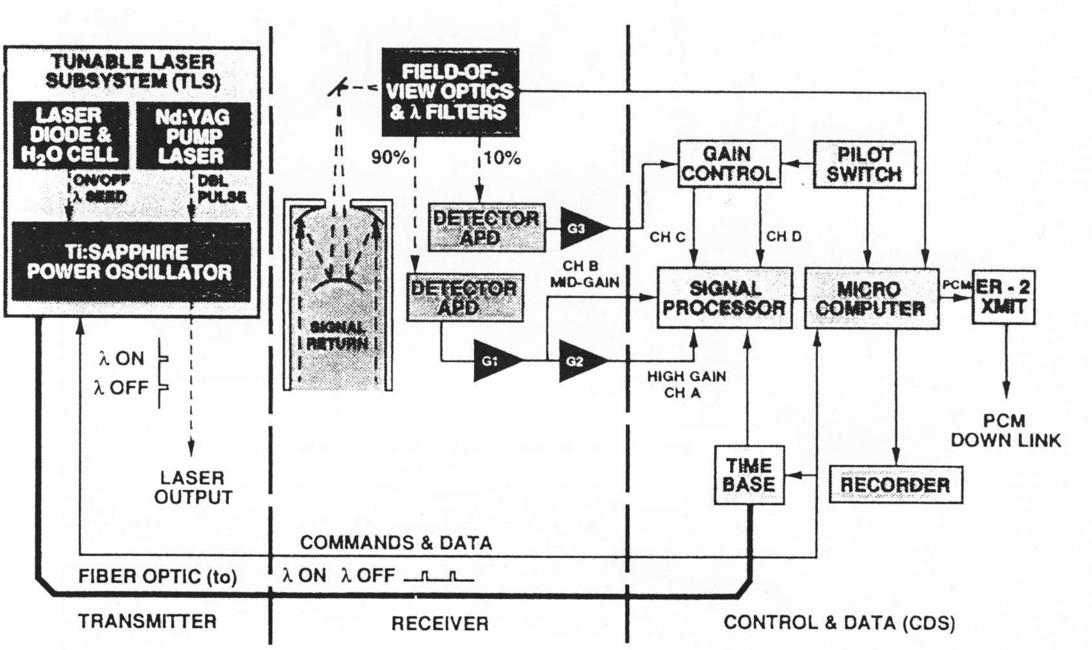
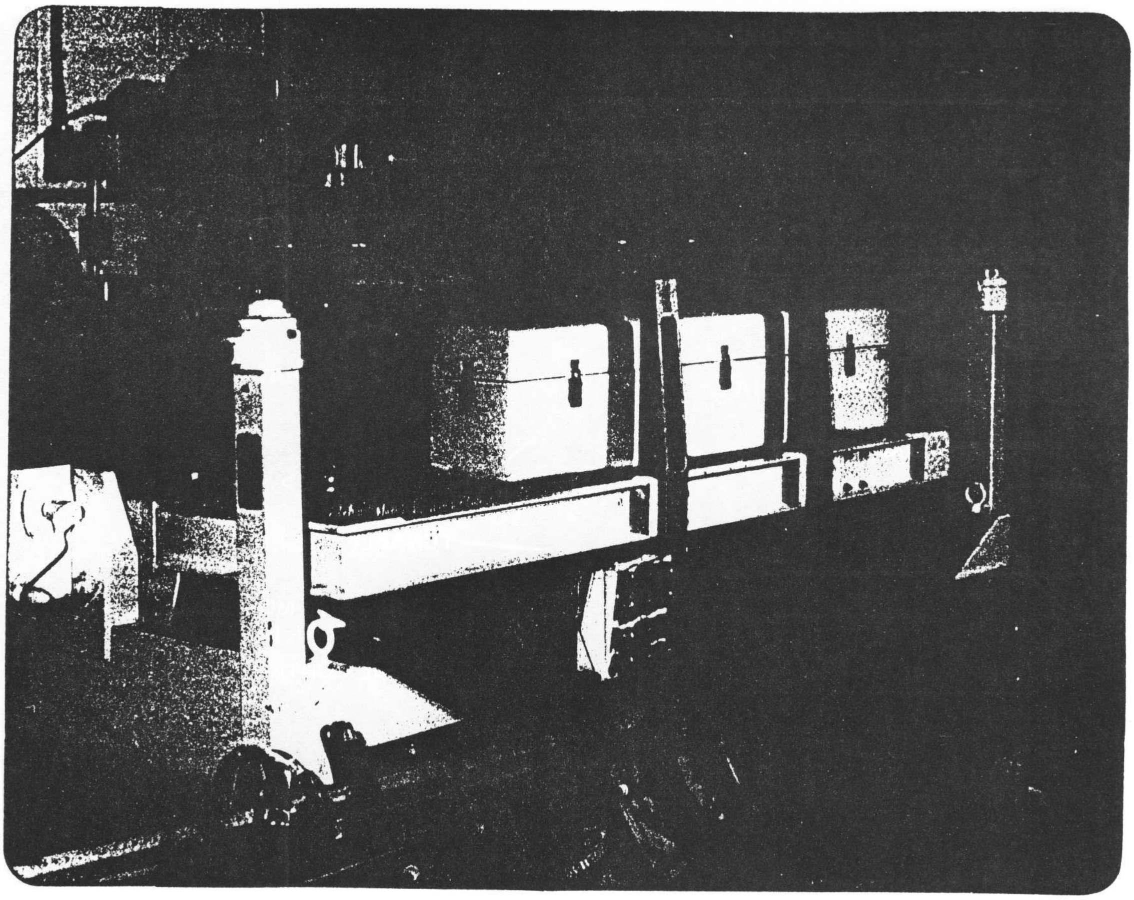
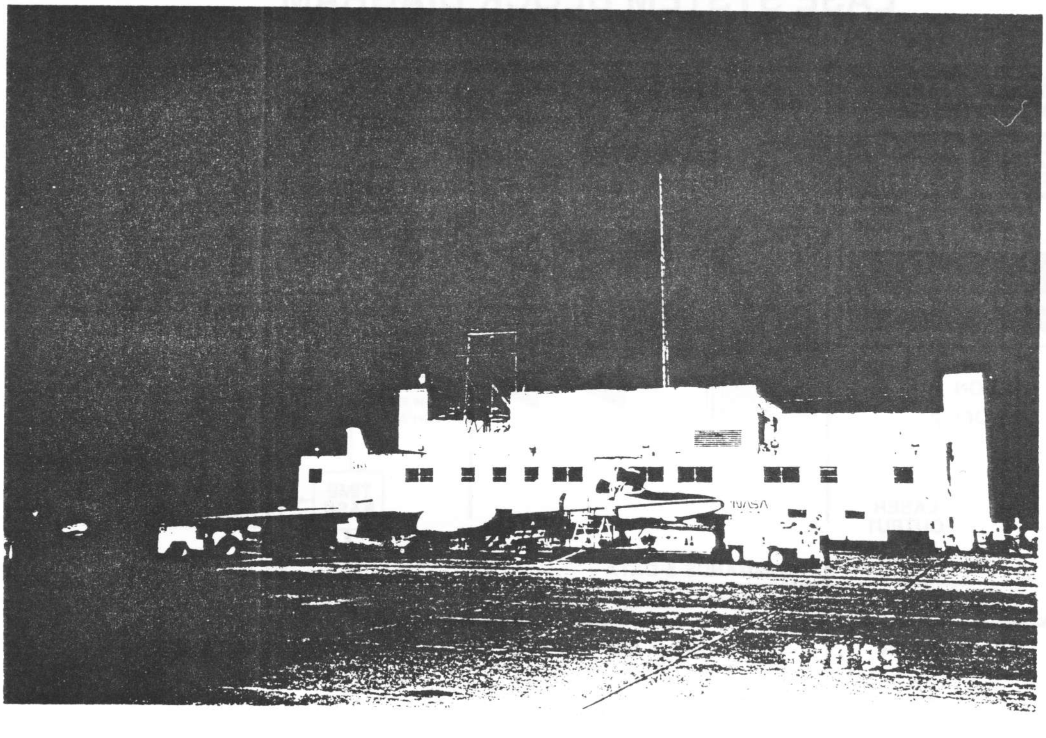


Figure 1.




NASA
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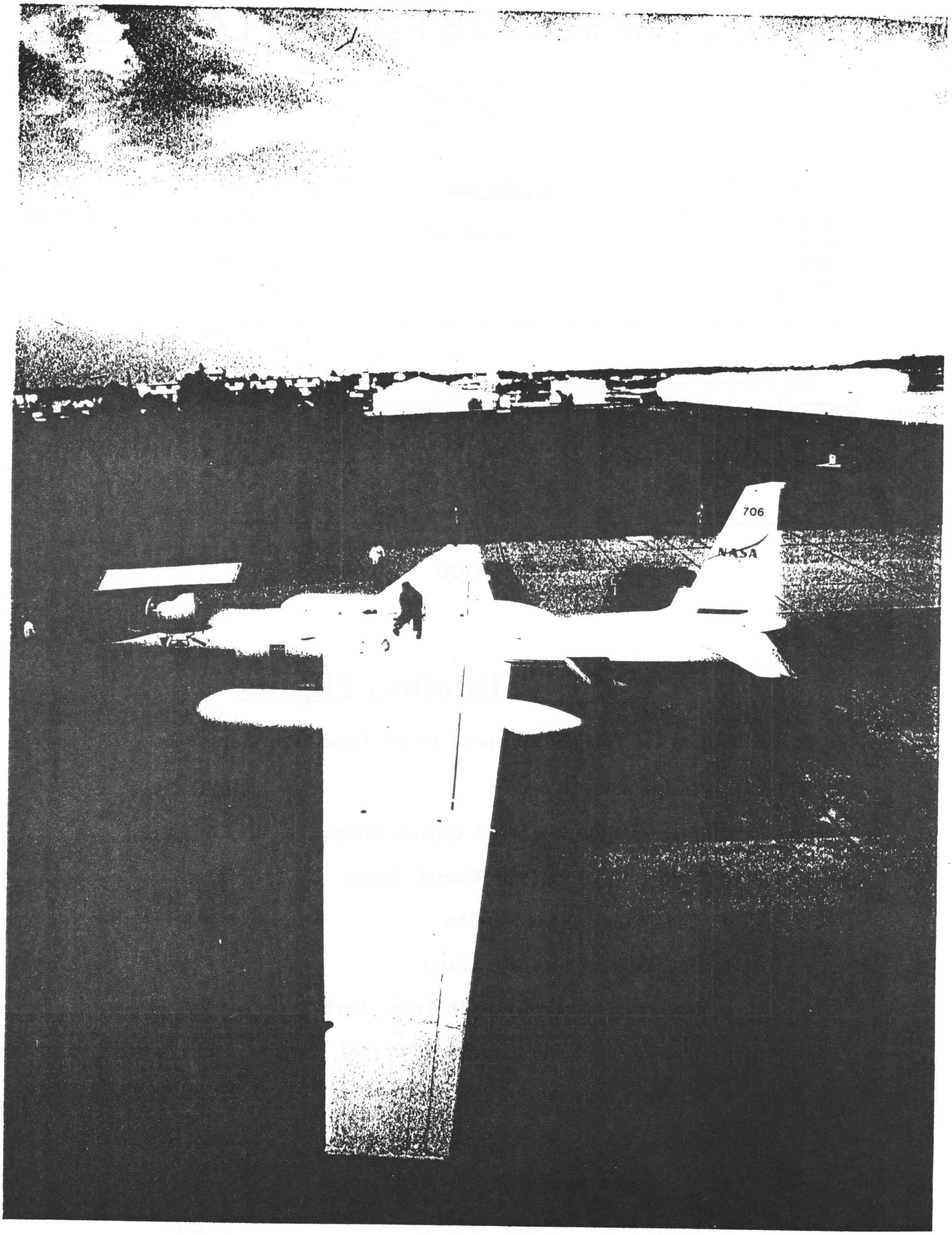
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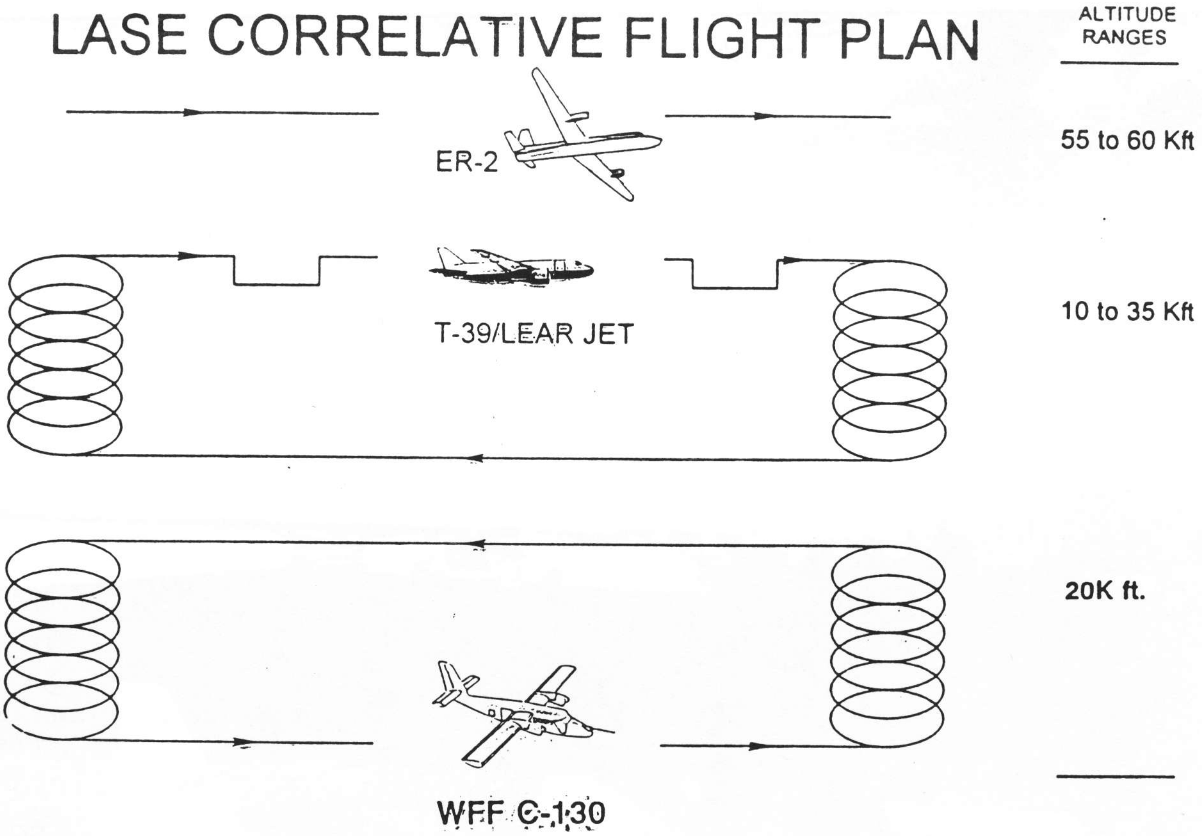
NASA

LASE CORRELATIVE FLIGHT PLAN

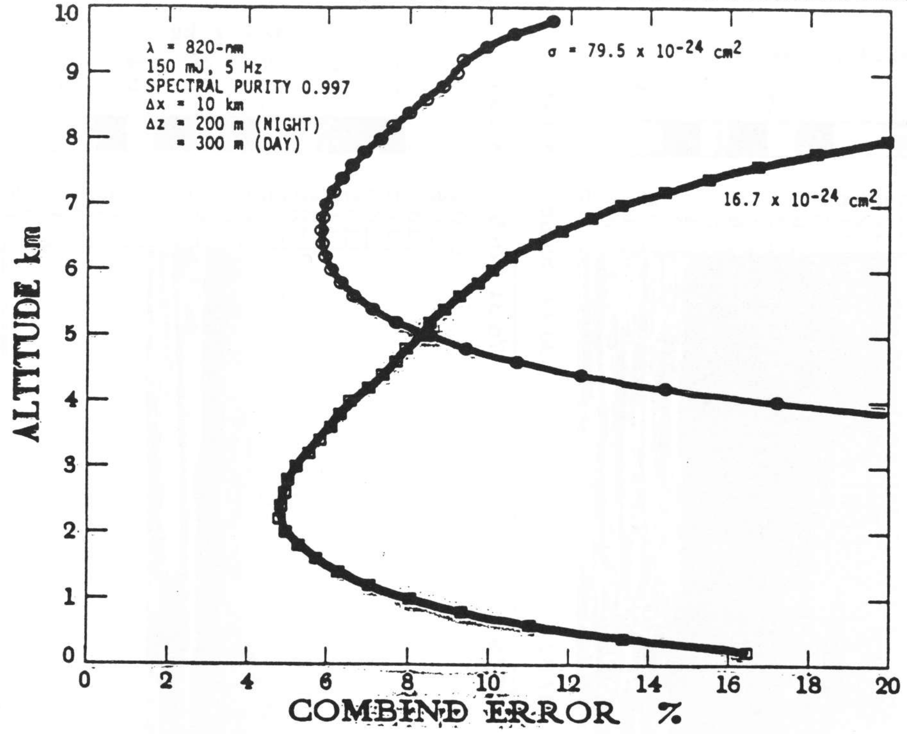


LASE Validation Flights

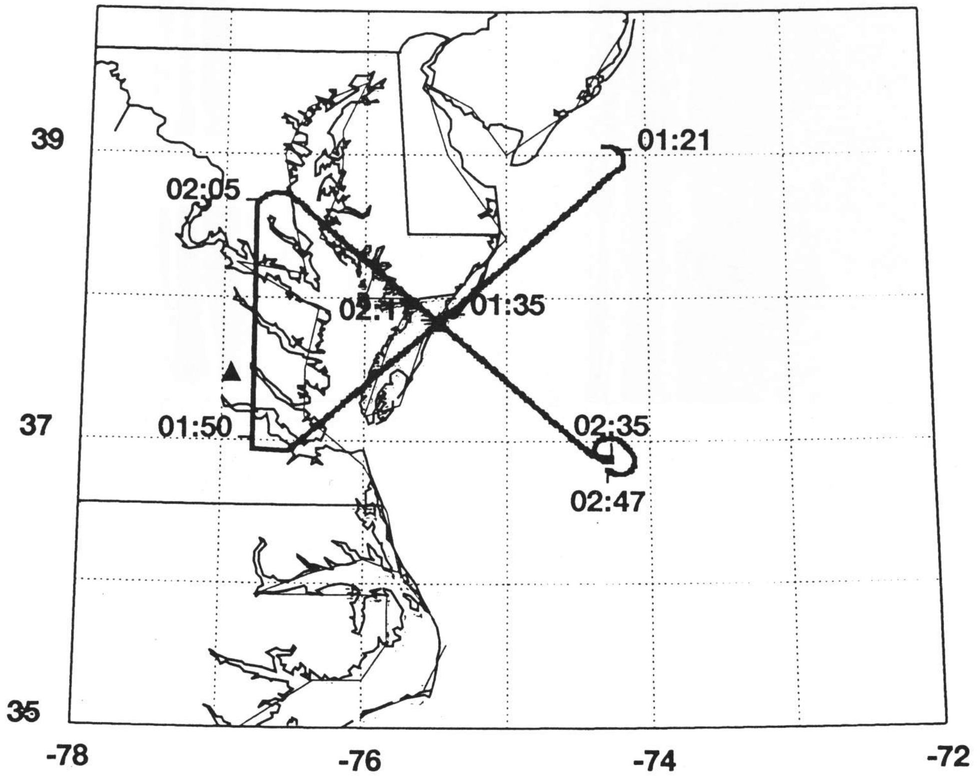
- Ten Flights for Total of 60 hrs of Flight Time From Sept. 8-26.
- LASE Mission Objectives:

LASE Mission Objectives	Flight No.
• Two - Nighttime WFF Correl. Meas.	1; 3
• Two - Daytime WFF Correl. Meas.	5; 6; 7
• Cold Front Cross Section	8; 9
• Sea Breeze Dev./Structure	5; 6
• Upper-Level Front/Strat.-Trop. Exch.	10
• Water Vapor Flux (Land & Ocean)	5; 6
• Cirrus Cloud Formation Study	1; 2; 3; 5; 7; 9
• DMSP/SSM-T2 Satellite Intercom.	1; 2; 5; 8; 9
• Hurricane Survey	2
• Large-Scale Meteor. Survey	8; 9; 10

LASE H2O DIAL SIMULATIONS A/C ALT 16 KM
COMBINED ERROR, RANDOM PLUS SYSTEMATIC

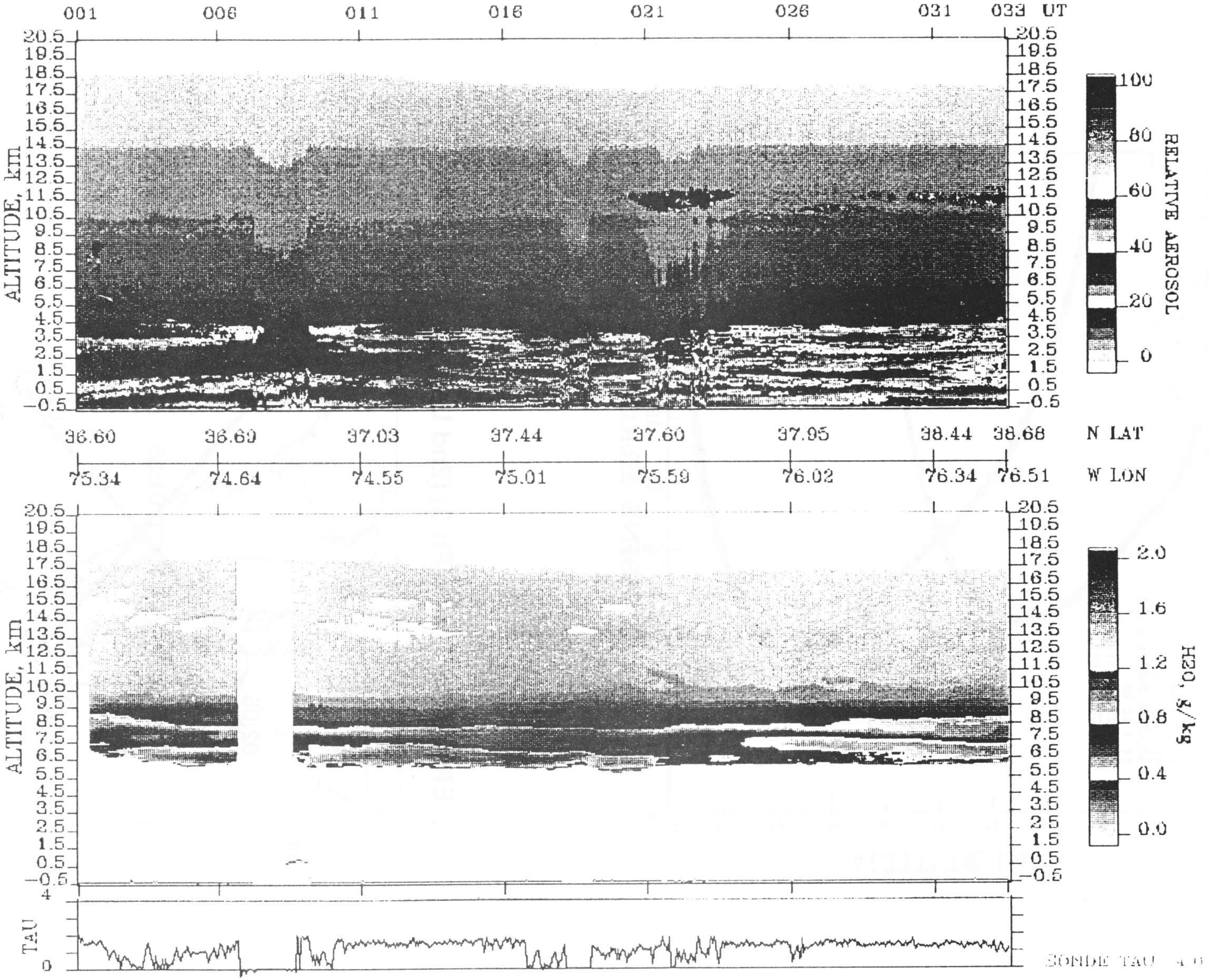


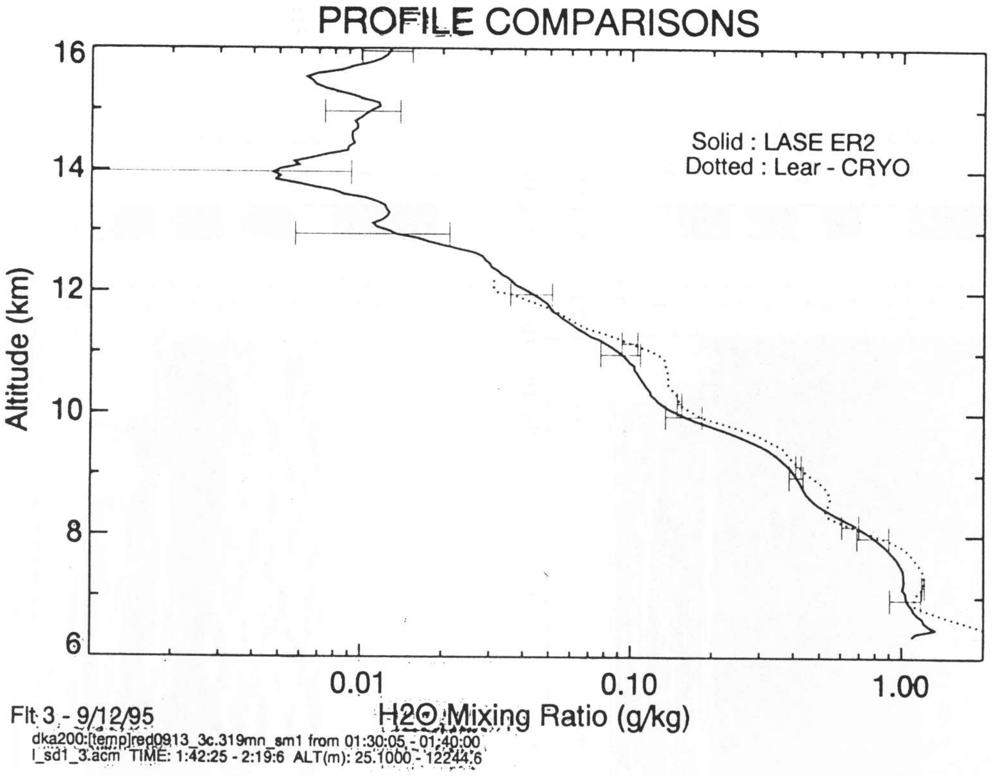
ER2 LASE Track (Flt 3) (2nd Leg) Sept. 12, 1995

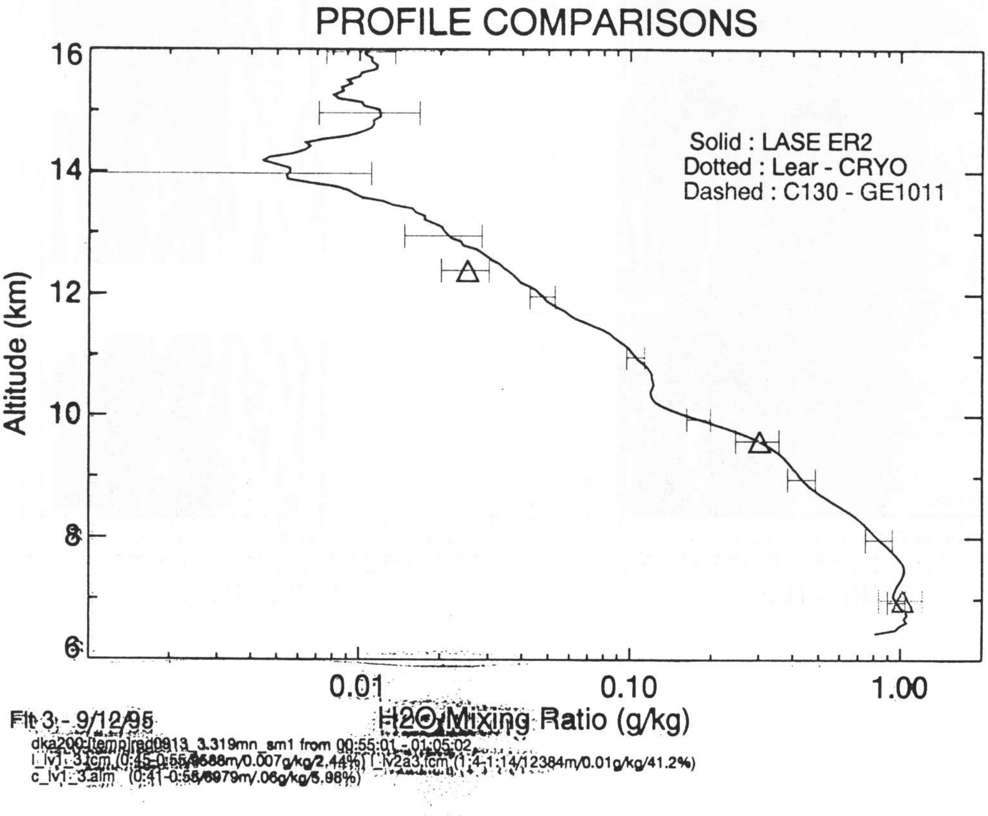


LASE VALIDATION 3

9/12/95

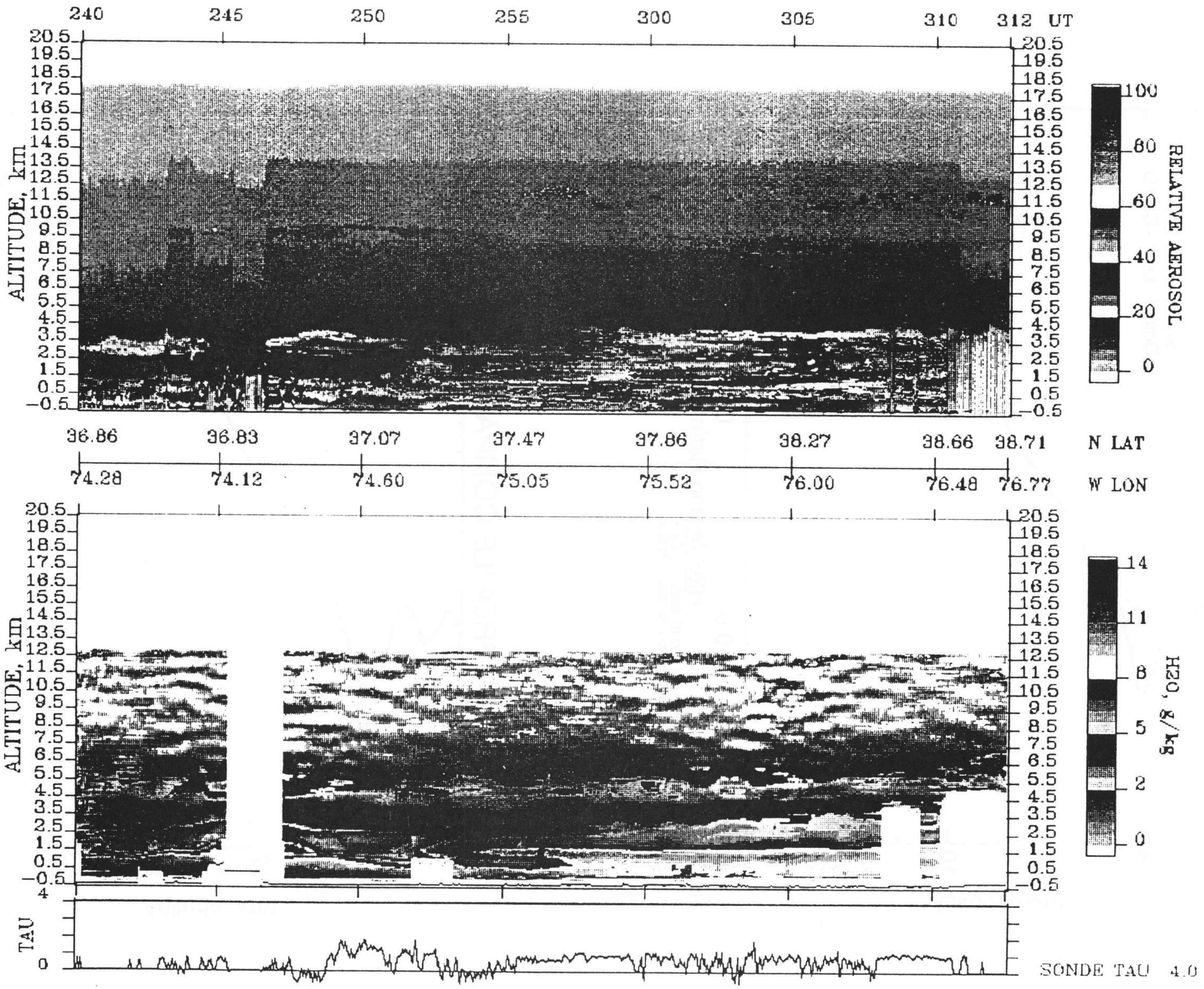


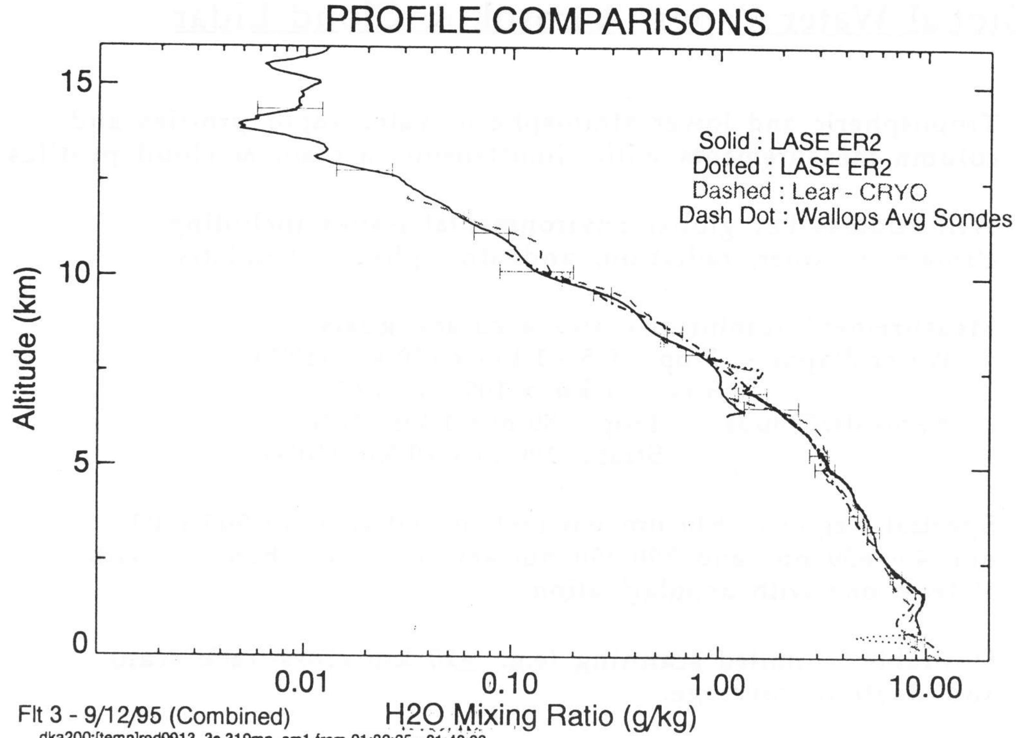

PROFILE COMPARISONS
Solid : LASE ER2
Dotted : Lear - CRYO
Altitude (km)
16
14
12
10
8
6
0.01
0.10
1.00
H2O Mixing Ratio (g/kg)
Flt 3 - 9/12/95
dka200:[temp]red0913_3c.319mn_sm1 from 01:30:05 - 01:40:00
l_sd1_3.acm TIME: 1:42:25 - 2:19:6 ALT(m): 25.1000 - 12244.6


PROFILE COMPARISONS
Solid : LASE ER2
Dotted : Lear - CRYO
Dashed : C130 - GE1011
Altitude (km)
16
14
12
10
8
6
0.01
0.10
1.00
H2O Mixing Ratio (g/kg)
Flt 3 - 9/12/95
dka200:[temp]red0913_3.319mn_sm1 from 00:55:01 - 01:05:02
l_lv1_3.cm (0:45-0:55/9588m/0.007g/kg/2.44%) l_lv2a3.tcm (1:4-1:14/12384m/0.01g/kg/41.2%)
c_lv1_3.alm (0:41-0:55/6979m/.06g/kg/5.98%)

LASE VALIDATION 3

9/12/95





Flt 3 - 9/12/95 (Combined)

dka200:[temp]red0913_3c.319mn_sm1 from 01:30:05 - 01:40:00
dka200:[temp]red0913_3c.319mn_sm1 from 02:55:04 - 03:05:05
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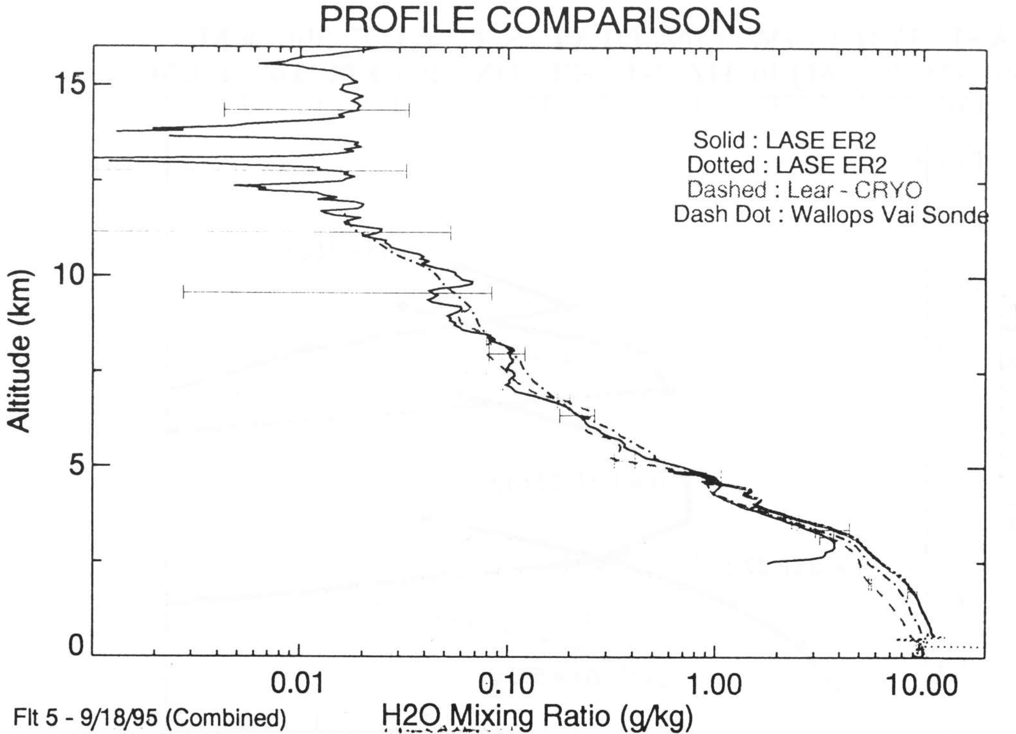


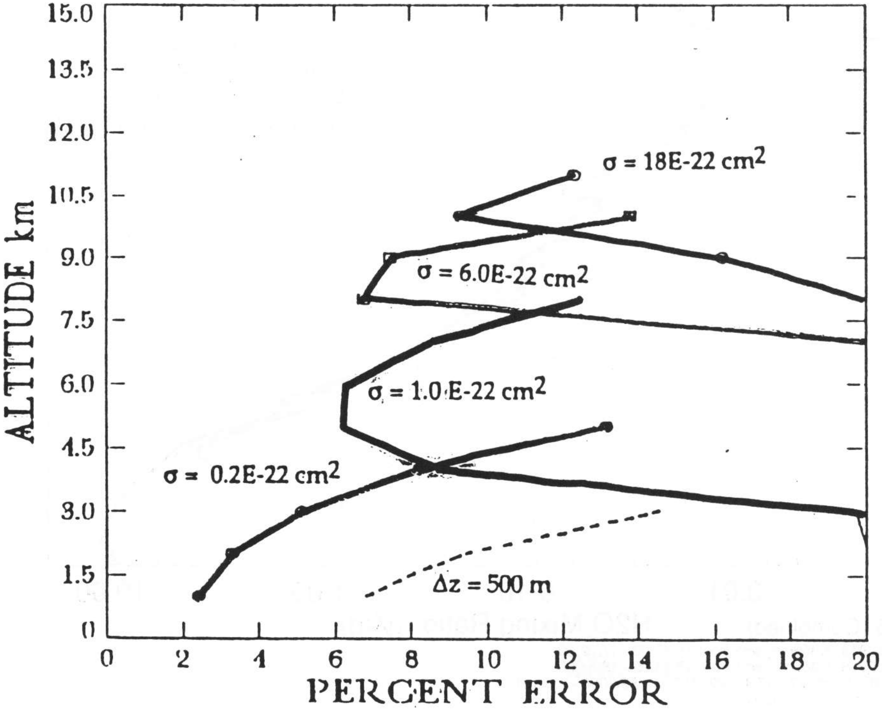
Flt 5 - 9/18/95 (Combined)

dka200:[temp]red0918_5.366mn_sm1 from 16:52:02 - 17:02:00
dka200:[temp]red0918_5.366mn_sm1 from 18:44:02 - 18:54:00
l_sd1_5.acm TIME: 17:26:-27 - 17:47:-22 ALT(m): 55.3000 - 9345.70
w_vai_5.asm ALT(m): 0 - 12210

Global Water Vapor, Aerosol, & Cloud Lidar

- Tropospheric and lower stratospheric water vapor profiles and column measurements with simultaneous aerosol & cloud profiles.
- Will address key global environmental issues including climate, weather, radiation, and atmospheric chemistry.
- Measurement resolutions and accuracy goals:
  Water Vapor - Trop.: 0.5 - 1 km x 100 km (10%)
  Strat.: 1 km x 100 km (20%)
  Aerosols/Clouds - Trop.: 50 m x 1 km (10%)
  Strat.: 100 m x 10 km (10%)
- Spectral Regions: 940 nm narrowband DIAL with 900-1100 nm, 450-650 nm, and 300-350 nm aerosol/cloud channels with at least one with depolarization.
- Desirable: Limited scanning (e.g., ±20 km cross-track scan) and daytime coverage.
- Deployment: Small satellite in polar, low Earth orbit with ~1 yr life

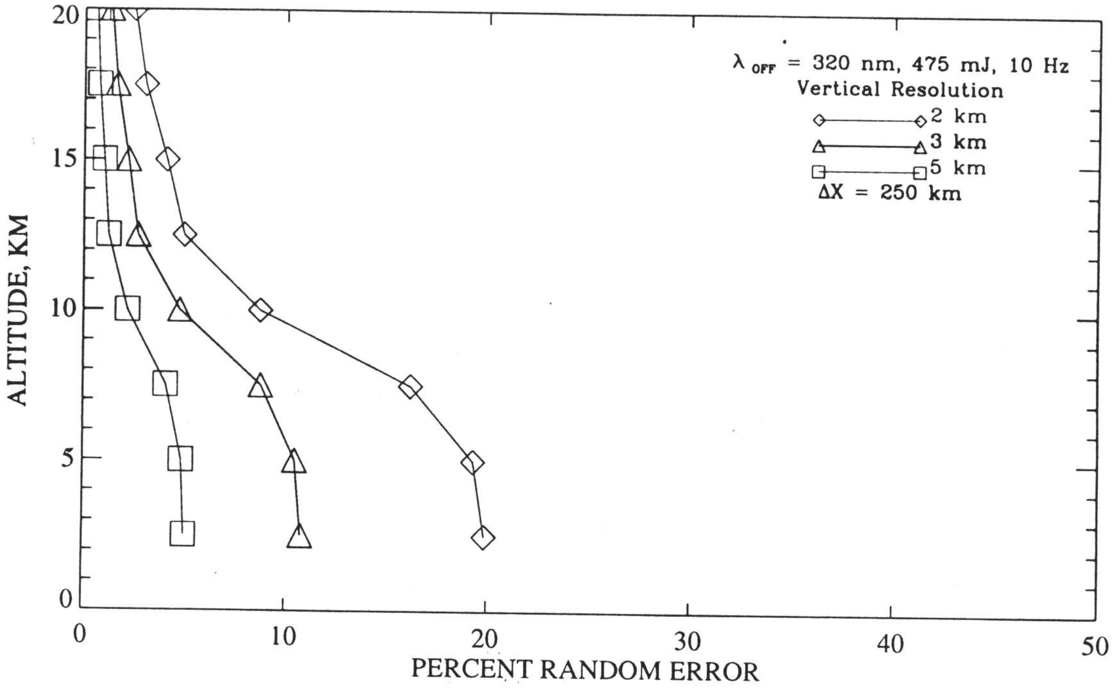
LASE FOLLOW-ON DIAL S/C ALT 350 KM
940-NM, 225 MJ,10 HZ, NIGHT, DX=100 KM, DZ=1 KM



Global Ozone, Aerosol, & Cloud Lidar

- Simultaneous tropospheric and stratospheric ozone profiles and column measurements with simultaneous aerosol & cloud profiles.
- Will address key global environmental issues including global change, ozone depletion, atmospheric chemistry, climate, atmospheric dynamics, and meteorology.
- Measurement resolutions and accuracy goals:
  - Ozone - Trop.: 3 km x 100 km (10%)
    - Strat.: 1 km x 100 km (5%)
  - Aerosols - Trop.: 60 m x 1 km (10%)
    - Strat.: 100 m x 10 km (10%)
- Spectral Regions: 305-320 nm with 10-12 nm $\Delta\lambda$ DIAL with two aerosol/cloud channels at λ_{off} and in 900-1100 nm or 450-650 nm region with at least one depolarization channel.
- Desirable: Limited scanning (e.g., ±20 km cross-track scan) and daytime coverage.
- Deployment: Small satellite in polar, low Earth orbit with ~1 yr life

NASA-CSA O_3 DIAL SIMULATIONS, S/C ALT. 350 KM
NIGHT BACKGROUND, U. S. STANDARD MODEL O_3



DIAL Remote Sensing of Gases and Aerosols

- Important atmospheric studies have been conducted using airborne DIAL measurements of ozone, water vapor, and aerosols.

- Advanced airborne DIAL systems have demonstrated the technology and techniques that are needed for the development of a spaceborne DIAL system.

- Atmospheric science missions and requirements for future spaceborne DIAL systems have been defined, and studies are underway that would lead to the development of a small-satellite-based DIAL system for the measurement of ozone and aerosols or water vapor, aerosols, and clouds.