Tunable Infrared Laser Sources for Spectroscopy and Atmospheric Trace Gas Detection

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Abstract

Recent advances in visible and near infrared diode laser technology and availability of new IR nonlinear optical materials permit the development of compact, all-solid-state CW narrowband infrared sources based on difference frequency generation. Sources operating in the 3 to 10 μm range and tunable over a frequency interval of up to 100 cm^{-1} can be fabricated and should be suitable for trace gas detection and monitoring in a wide variety of applications. The design issues involved in the development of such sources will be addressed, in particular the use of semiconductor amplifiers and optical build-up cavities to boost the available IR power. Specific sensor characteristics for trace gas detection including operating wavelength, tuning range, output power, sensitivity, and noise reduction will be discussed. Successful operation of two such tunable IR sensors operating near 3 μm and 5 μm has been demonstrated. The application of these diode laser pumped infrared sources to detection of environmentally important gas species such as methane and carbon monoxide, respectively, will be described.

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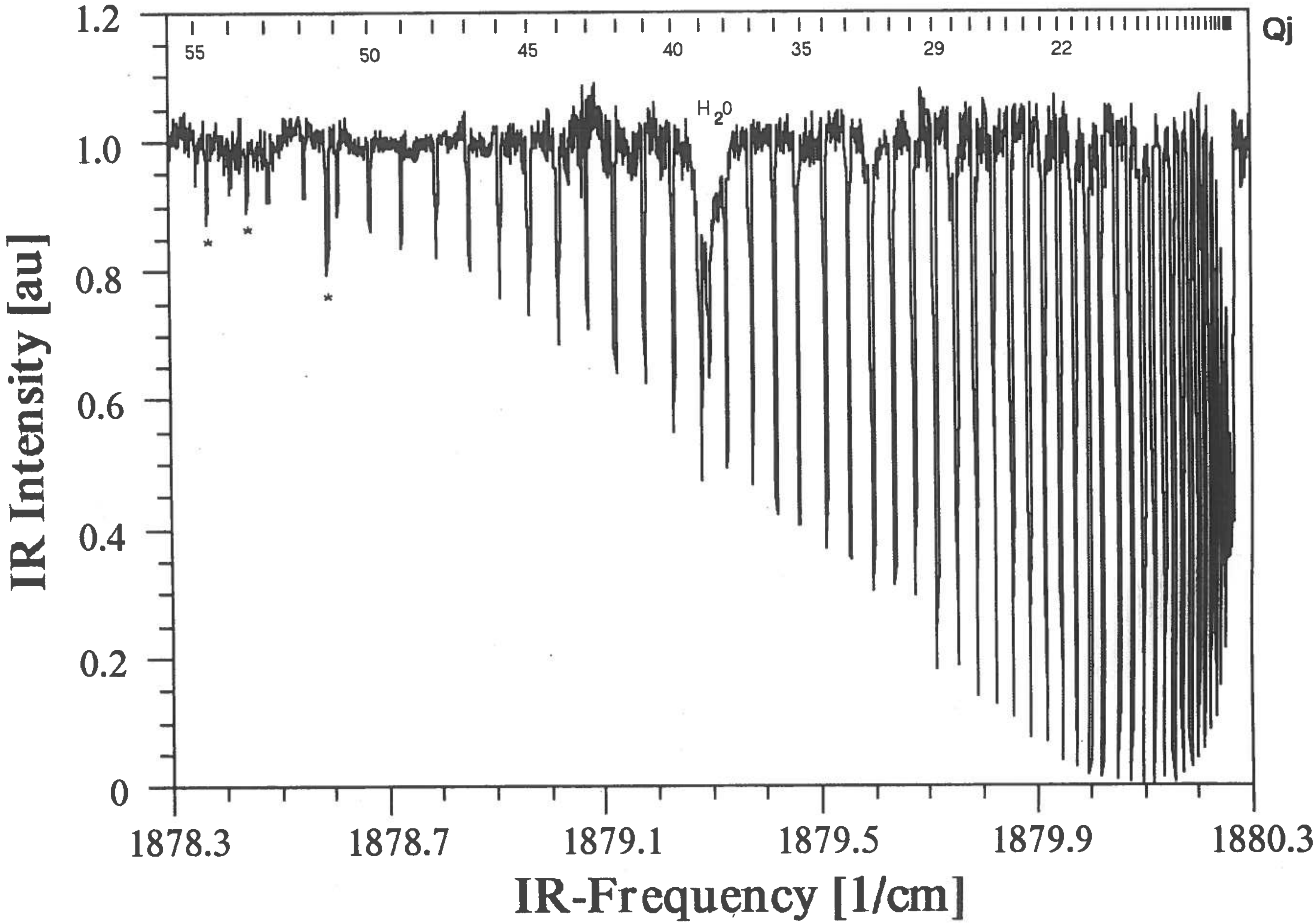
Outline

* Motivation and Main Concepts
* Advanced Difference-Frequency Spectroscopic Sources
* Detection of Trace Gas Species
* Future Prospects

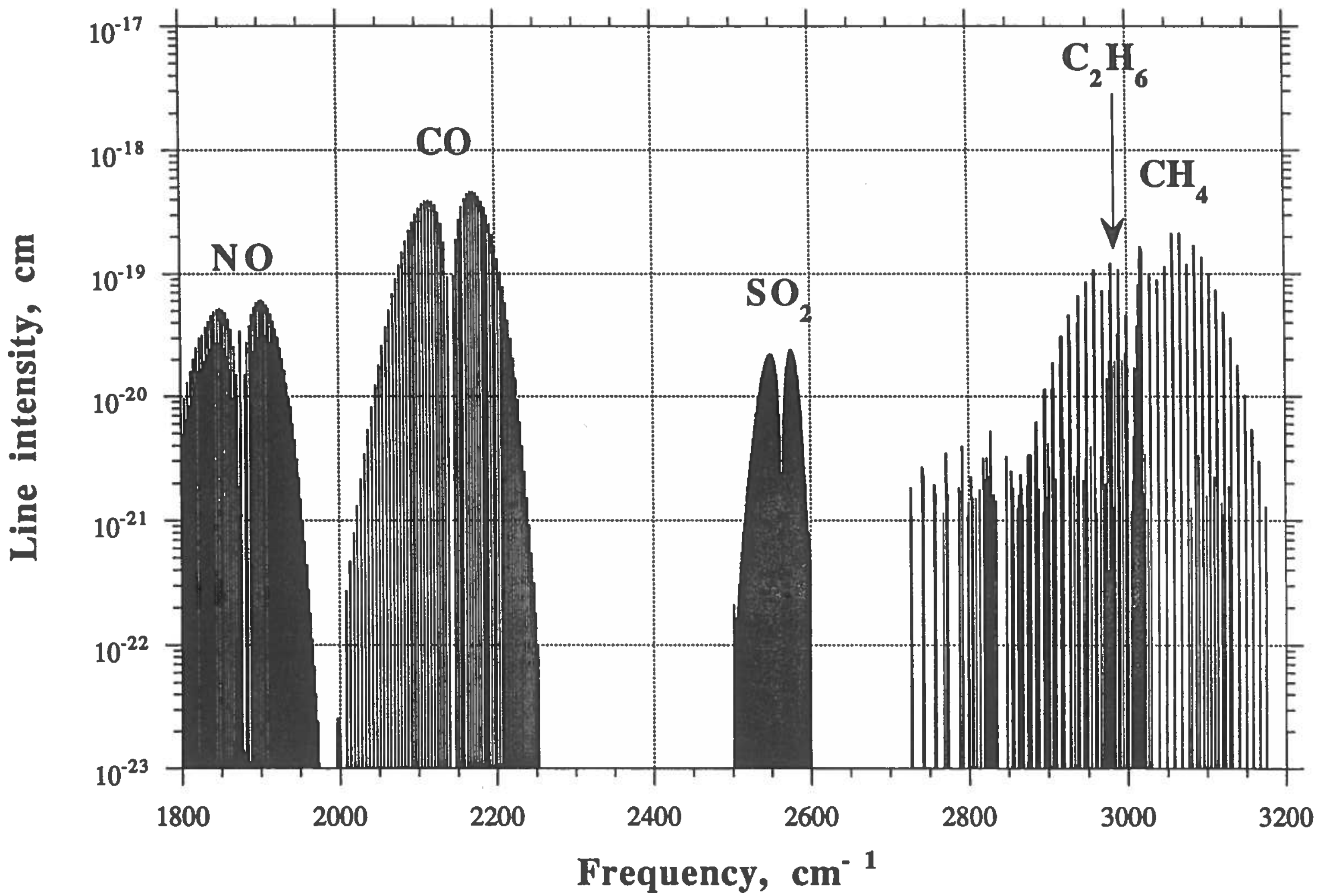
Motivation

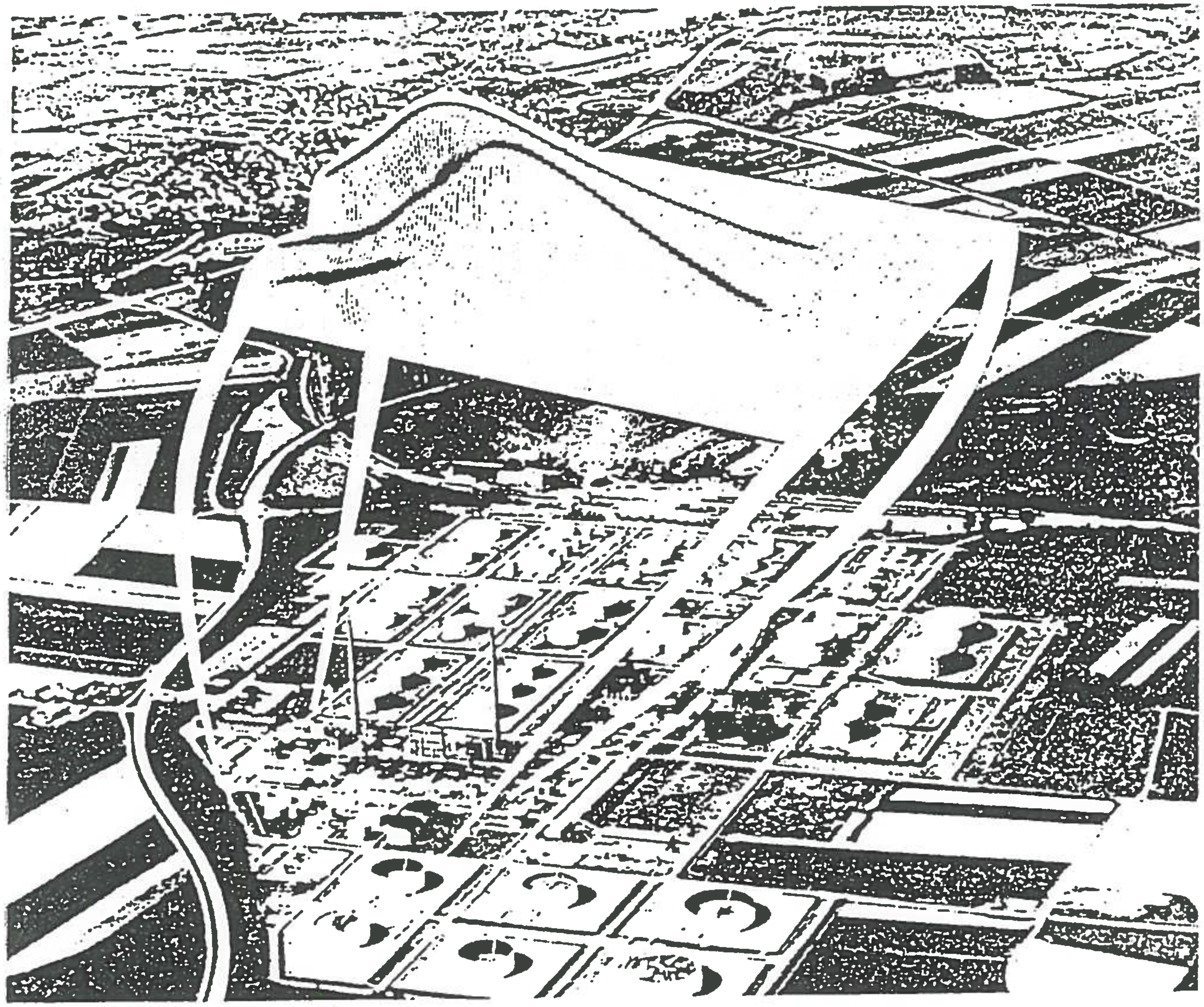
* Infrared Laser Spectroscopy
  - Ability to Do *in situ* Non-Intrusive Probing
  - Time Resolved Studies – Convenient
* Environmental Monitoring
  - Urban Air Monitoring
  - Rural Air Monitoring
  - Spacecraft Cabin Monitoring
  - Volcanoes
  - Industrial Applications
  - Chemical Plants and Oil Refineries
* Chemical Analysis and Process Control
* Aircraft Identification
* Medical Applications

Survey Absorption Spectrum of N_2O



Absorption spectra of some important atmospheric pollutants





Remote Sensing Using Lasers. With lasers it is now possible to detect minute traces of chemicals from a distance. In environmental and energy programs the new techniques can be used to detect pollutants in the atmosphere sensitively and rapidly, to study aerosols and smog, to measure turbulence and wind velocity, and to monitor the stratospheric ozone layer. The techniques can also be employed to study combustion in a furnace or in engines while they operate. The illustration shows a blown-up three-dimensional map of the concentration of ethylene glycol that has leaked to the atmosphere from an oil refinery in Germany. The map is superimposed on an aerial photograph of the refinery. (The long arrows illustrate the points on the ground that correspond to the corners of the map.) The gas leak was mapped with a laser 0.5 kilometer away from the plant. The sensitivity of the measurement is 20 parts in 10^9. The peaks in the map reveal two sources of escaping gas. The gas is not coming from the two smokestacks that can be seen in the photo, however; the sources were pinpointed to be two leaks in separate buildings. (Photo courtesy of Max-Planck-Institute for Quantum Optics, Garching, Federal Republic of Germany.)

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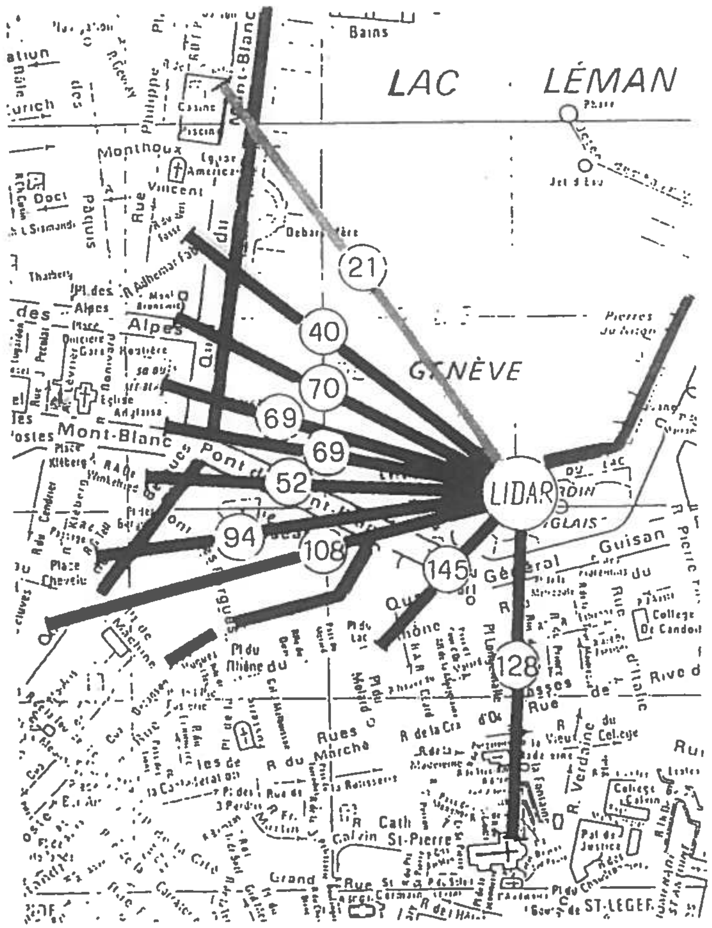
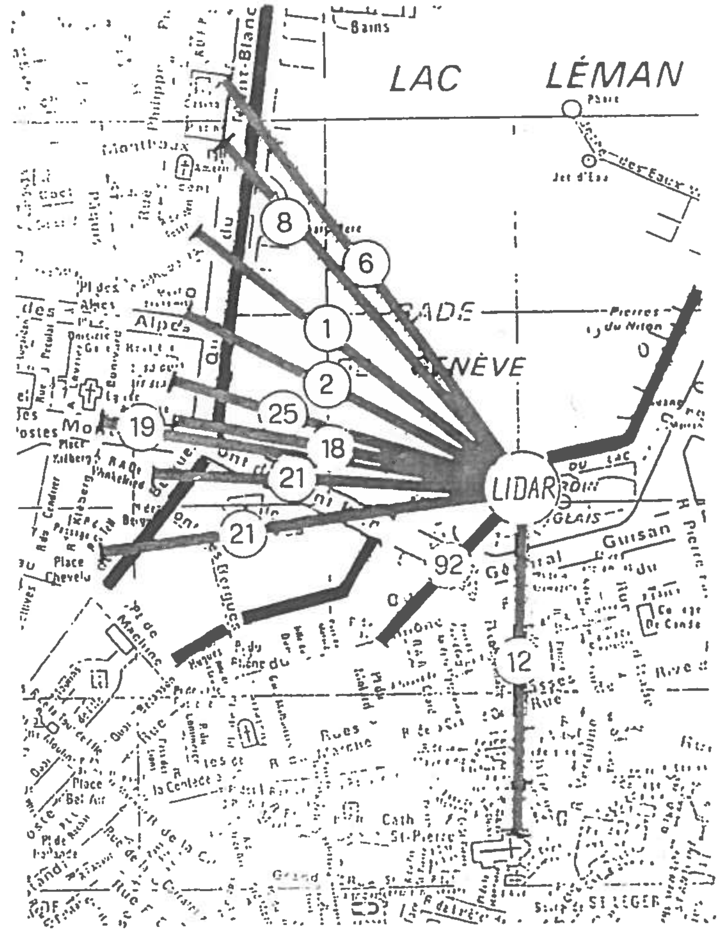


strong smog situation



clean air situation 3 days later

LIDAR measurement of NO_2 in Geneva/Switzerland. Note the extremely high pollutant concentration on the right: the area of a recreational park covers the hidden exhaust of an underground parking garage.

U.S. Forest Service

FOREST FIRE: A firefighter battles the 1992 inferno that consumed 257,000 acres of the Boise (Idaho) National Forest.

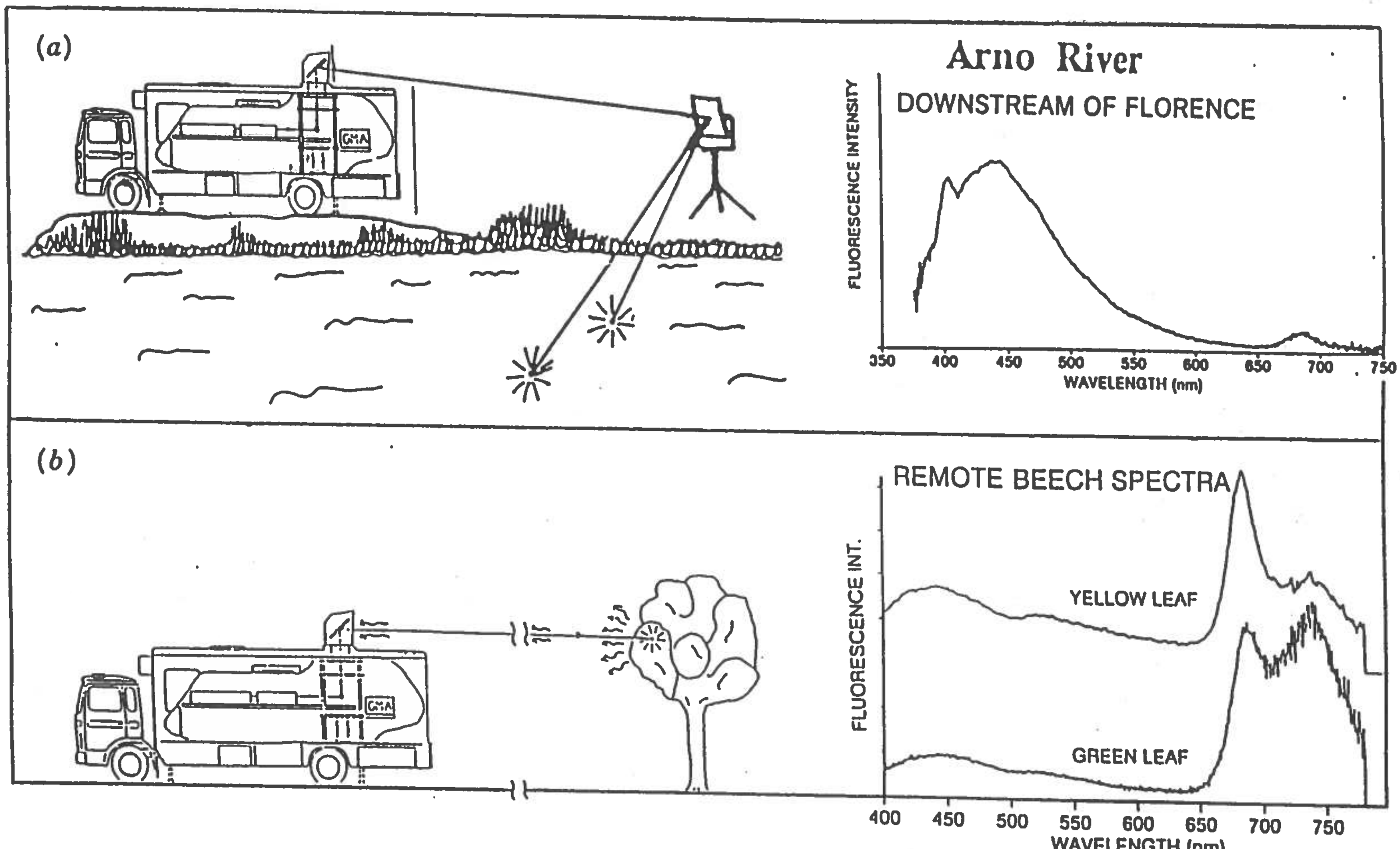
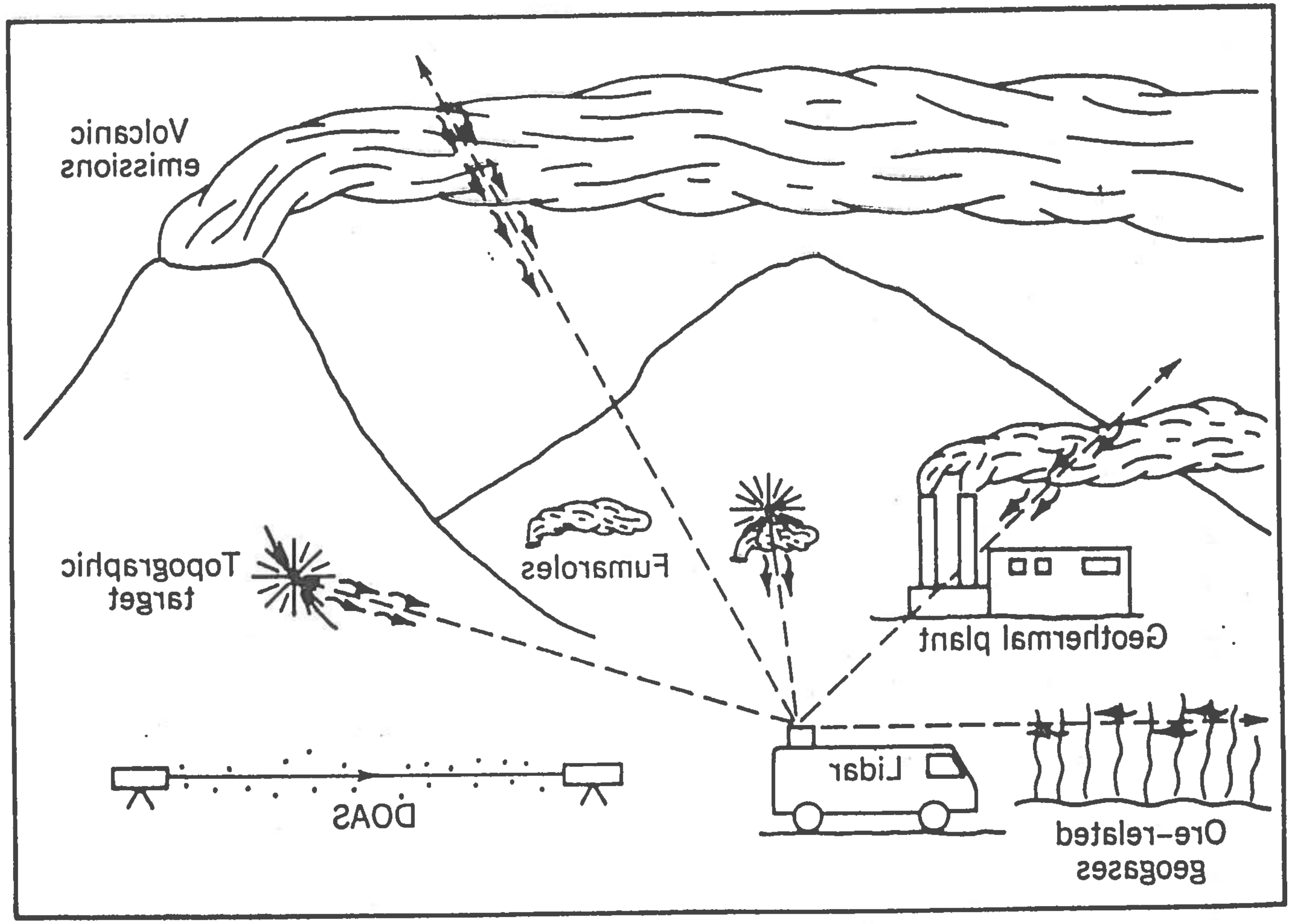
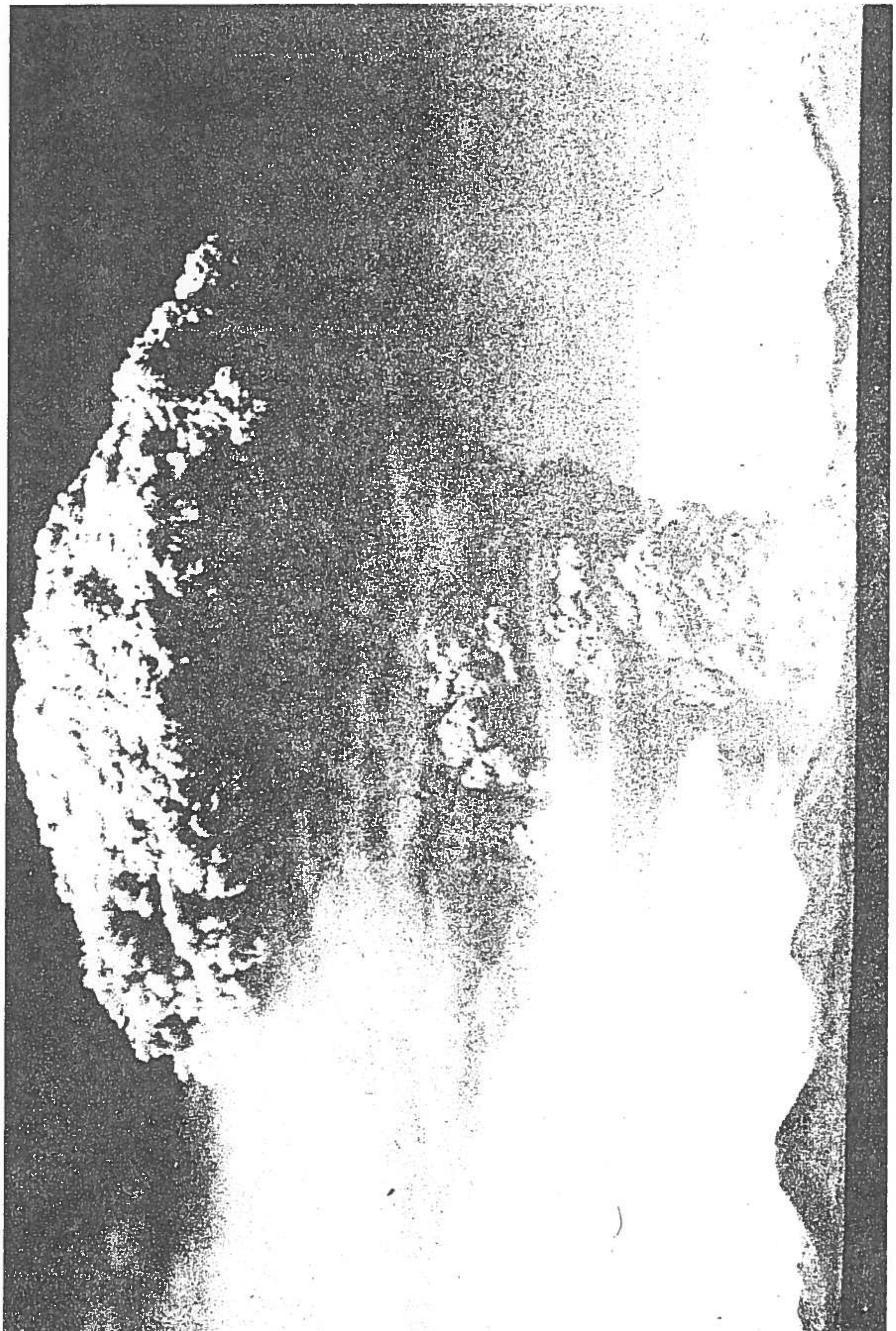
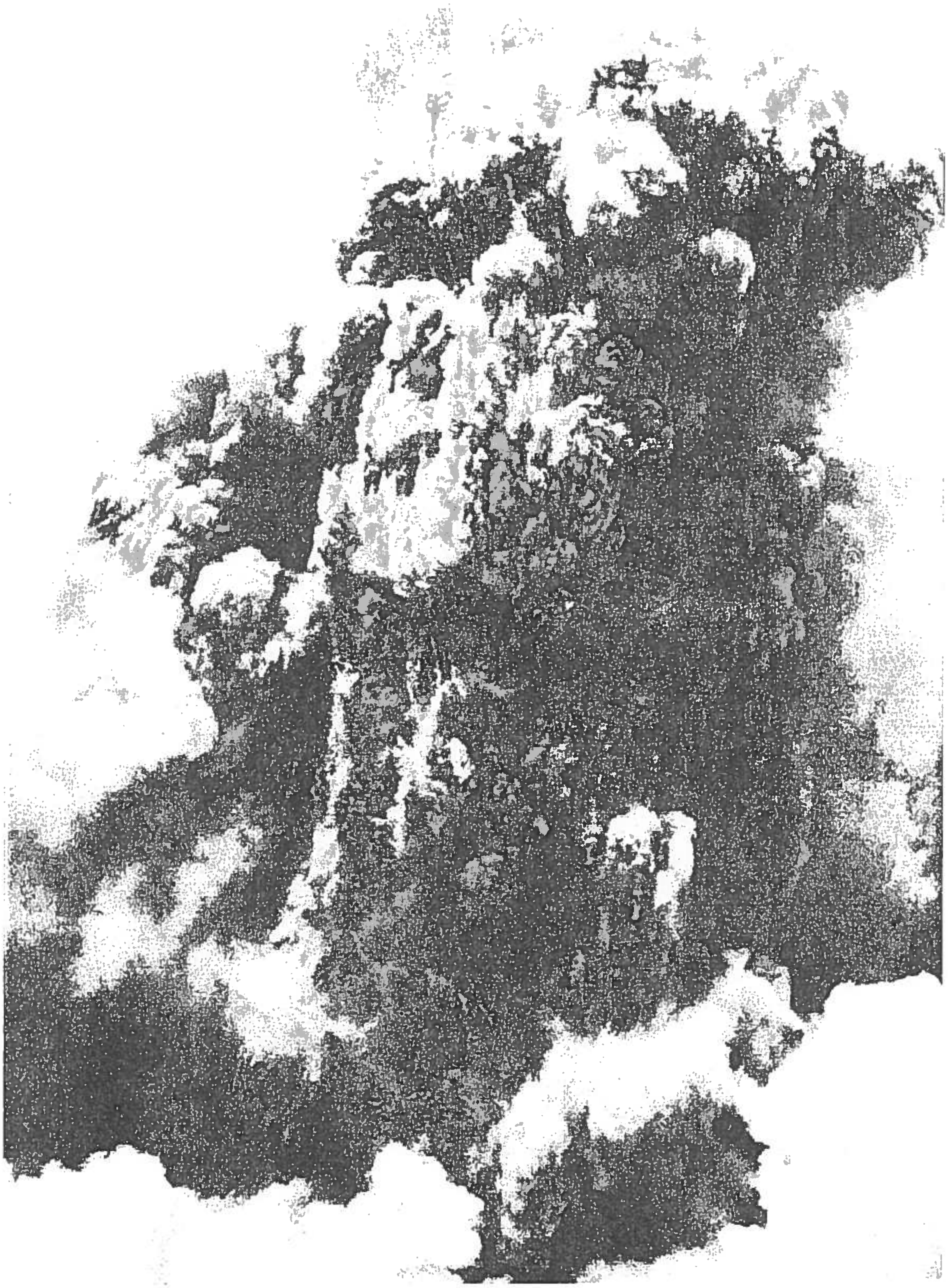


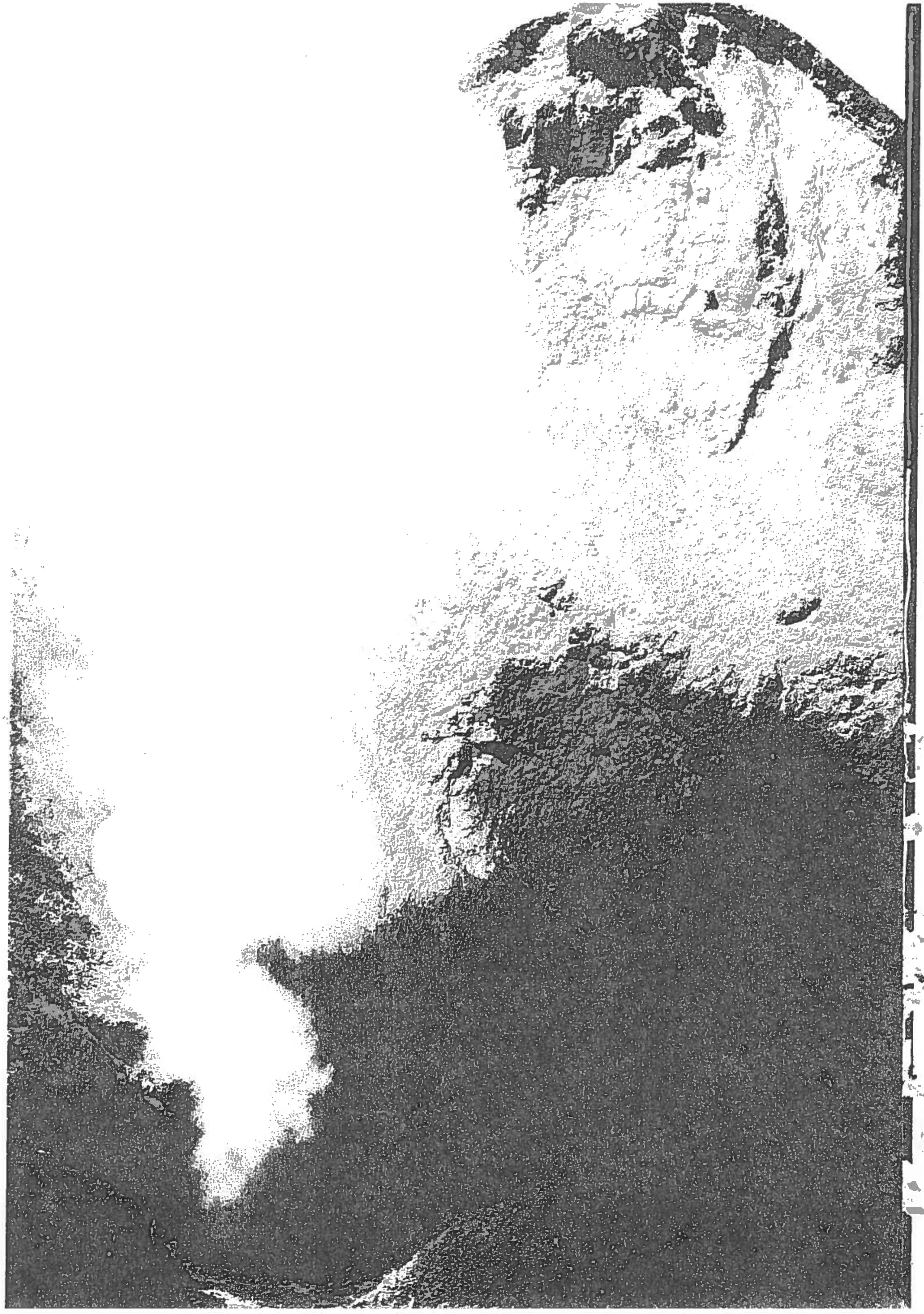
Figure 3.15. Fluorescence lidar measurements of (a) water and (b) terrestrial vegetation. A frequency-tripled Nd:YAG laser operating at 355 nm was used. Remote laser-induced fluorescence spectra are shown for a measurement distance of about 50 m. Adapted from Edner et al. (1992d,e).



Measurement scenarios for atomic mercury of geophysical origin. From Svanberg (1991).







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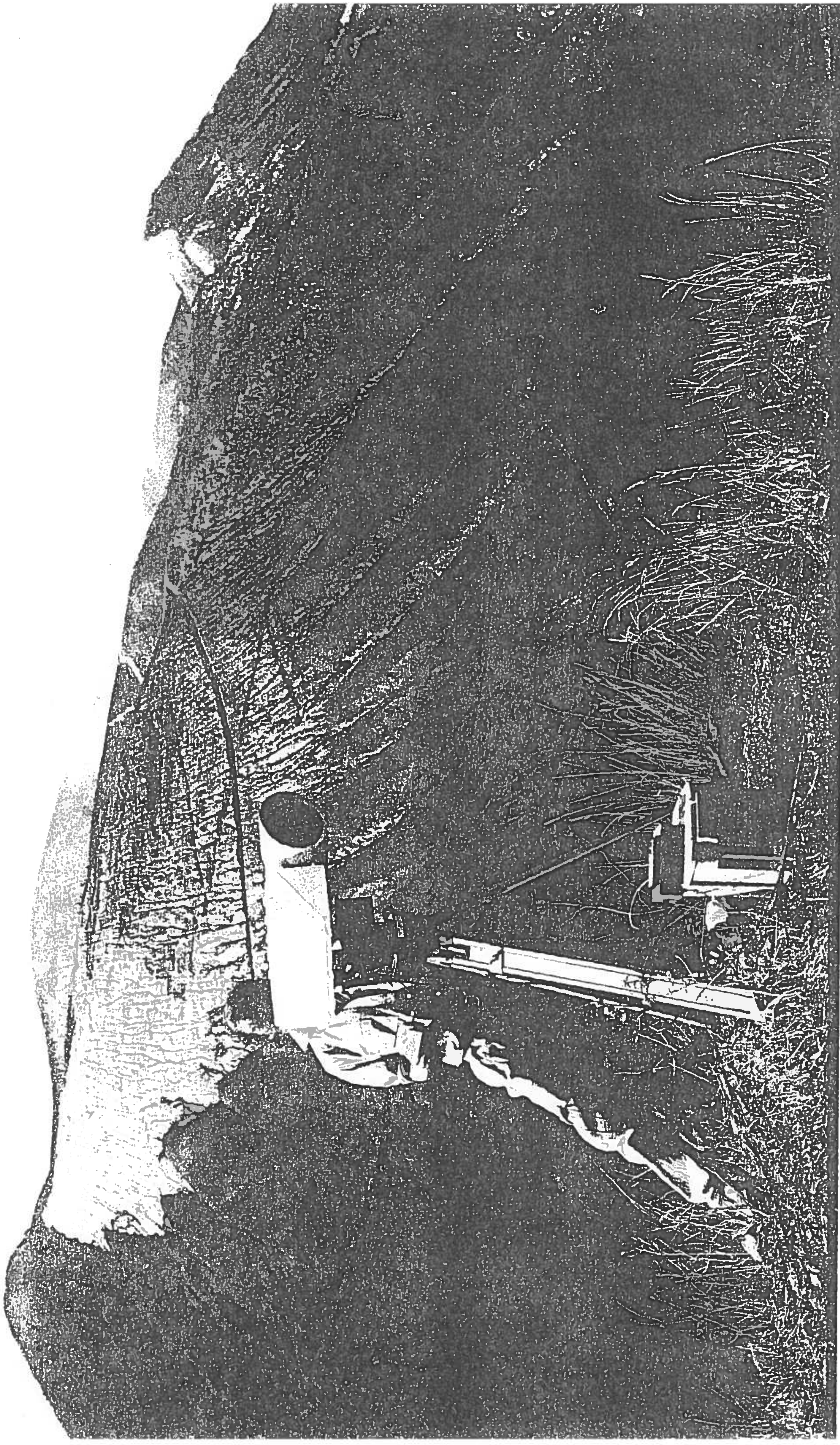
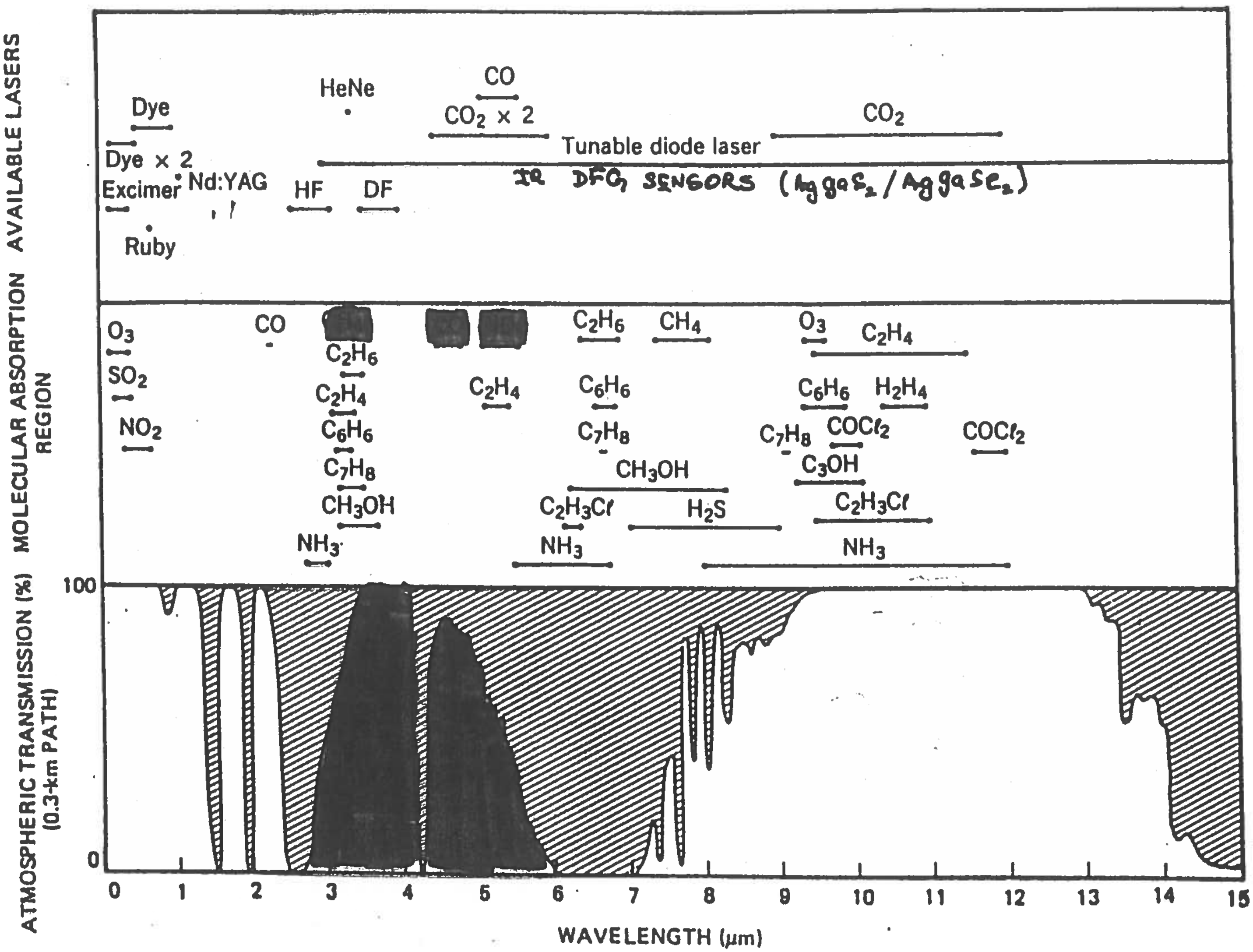


long path gas mon

SO_2

laser

1886



Atmospheric transmission, pollutant absorption bands, and available laser sources. From Grant and Menzies (1983).

Tunable CW IR Laser Sources

* **Color Center Lasers**
  Tunable (1-4 μm)
  Low temperature needed

* **Lead Salt Diode Lasers**
  Tunable (3-30 μm)
  Each diode ~100 cm^{-1}
  Undesirable discontinuities (mode hops)
  Low temperature needed

* **Tunable III-V Semiconductor Diode Lasers**

* **CO and CO_2 Sideband Lasers**
  Only discrete tunability: 5.1-6.4 μm, 9-11 μm

* **Difference Frequency Generation (DFG)**
  Tunable: 2-4 μm ($LiNbO_3$), 3-9 μm ($AgGaS_2$)
  1974 1991 (2 tunable lasers)
  Room Temperature

* **Optical Parametric Oscillators (OPO)**
  Tunable 2-4 μm ($LiNbO_3$, KTP, BBO) 100mJ, ns, ps, fs.
  Pulsed, stable cw operation difficult

Difference-Frequency Generation

* Advantages
  - Broad tunability (2 μm to 18 μm)
  - Narrow linewidth (better than 500 kHz)
  - CW or pulsed operation
  - No pump threshold
  - Availability of compact and stable pump sources

* Drawbacks
  - Low power

* Improvements
  - Cavity enhancement
  - Semiconductor power amplifiers
  - Quasi-phase-matched mixing crystals
  - Tapered waveguide quasi-phase-matched crystals

Difference Frequency Generation Offers a New Technique in IR High Resolution Spectroscopy

	Difference Frequency	Color Center Lasers	IR Diode Lasers	FTIR	IR Grating Spectrometer
Resol. (cm^{-1})	0.0001	0.0001	0.0001	1.0-0.002	1.0-0.05
Range (μm)	2.0-17	0.8-3.6	3.0-30	0.5-100.0	1.0-10.0
Divergence	1-5 mRad	1.2 mRad	>10 Deg	N.A.	N.A.
Output Power	1-100 μW	1-500 mW	$\sim$100 μW	N.A.	N.A.
Source Noise	high	high	low	low	low
Cost	moderate	high	high	moderate to high	moderate