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SMR/760-63

"College on Atmospheric Boundary Layer
and Air Pollution Modelling"
16 May - 3 June 1994

"Lasers for Environmental Monitoring"

A. MARZORATI
ENEL
Milan, Italy

Please note: These notes are intended for internal distribution only.

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LASERS FOR ENVIRONMENTAL MONITORING

A. Marzorati (ENEL-Milano)

ICTP, Miramare - Trieste

June 2nd, 1994

SUMMARY OF THE PRESENTATION

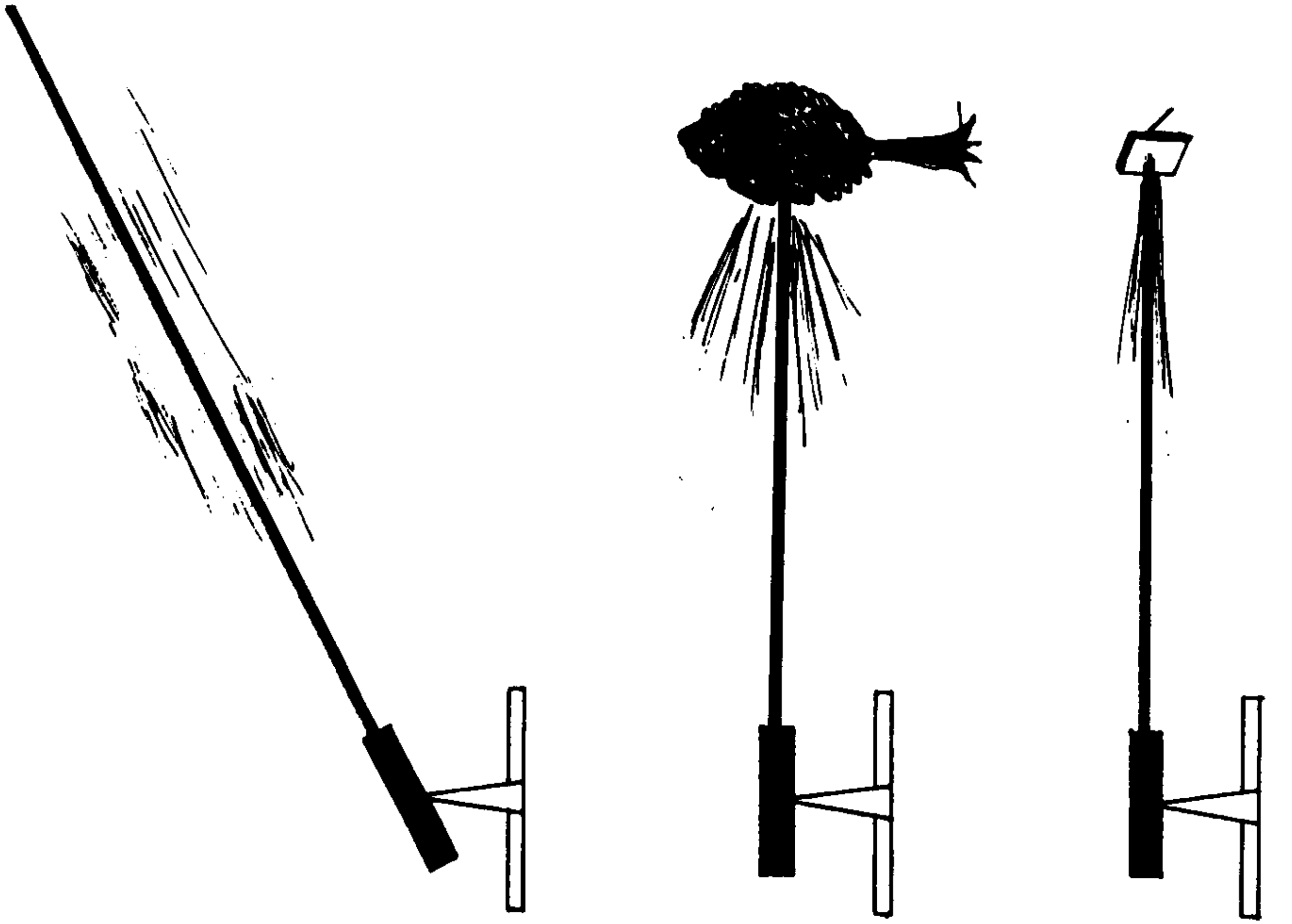
- Historical Background of Optical Remote Sensing
- Laser Remote Sensing of the Atmosphere - Scattering, Absorption
- Principle of the DIAL Method
- ENEL UV-DIAL System
- Calibration/Intercomparison with Other Similar and/or Different Devices
- Use of the DIAL System in Different Fields of Application with Different Objectives

SUMMARY OF THE PRESENTATION (continue)

- Industrial Areas (Plume Tracking, Sulphur Dioxide GLCs)
- Urban Areas (Vertical Profiles)
- Volcanic Areas (Flux Measurements)
- Comparison of Measured Data with Outputs of Mathematical Models
- Work in Progress in the Field of Optical Remote Sensing (ENEL-CISE)
- Film on Sostanj Campaign

Short History of Laser Remote Sensing

- 1960 (First Ruby Laser)
- 1963 (First LIDAR using a Ruby Laser)
  - Fiocco et al., Lygda et al.
- 1966 (DIAL for Water Vapour)
  - Schotland
- 1967 (RAMAN LIDAR O2 and N2)
  - Leonard et al.
- 1969 (Stratospheric Na)
  - Bowmann (Fluorescence LIDAR)
- 1970 (Pollutants with a RAMAN LIDAR)
  - Inaba and Kobayasi
- 1973 (Pollutants with a DIAL System)



Optical Techniques for Environmental Monitoring

- ABSORPTION
  - FTIR
  - DOAS
  - DIAL (UV - VISIBLE - IR)
  - DIODE LASERS
- FLUORESCENCE
  - LIDAR
  - ANALYZERS
- RAMAN
  - LIDAR
- SCATTERING
  - AEROSOLS
  - WIND SPEED

Table 4

Field Applications of DIAL

	UV	VIS	Near IR	Middle IR
Troposphere (0-10km)				
Pollutants	O_3, NO, Hg, SO_2, Cl_2	NO_2		CH_4, HCl, NH_3, SF_6, C_6H_6, O_3, C_2H_4, N_2H_4, CO, N_2O, CO_2,
Meteorology			H_2O, p^+, T^+	H_2O
Airborne	O_3, SO_2		H_2O	SF_6
Stratosphere (10-20km)				
On ground	O_3			
Airborne	O_3			
Space-borne (prospective)	O_3		H_2O, p^+, T^+	

+ the measurements of p and T can be performed by measuring the absorption on the center and wings of oxygen absorption lines in the NIR

LIDAR Systems for the Atmosphere

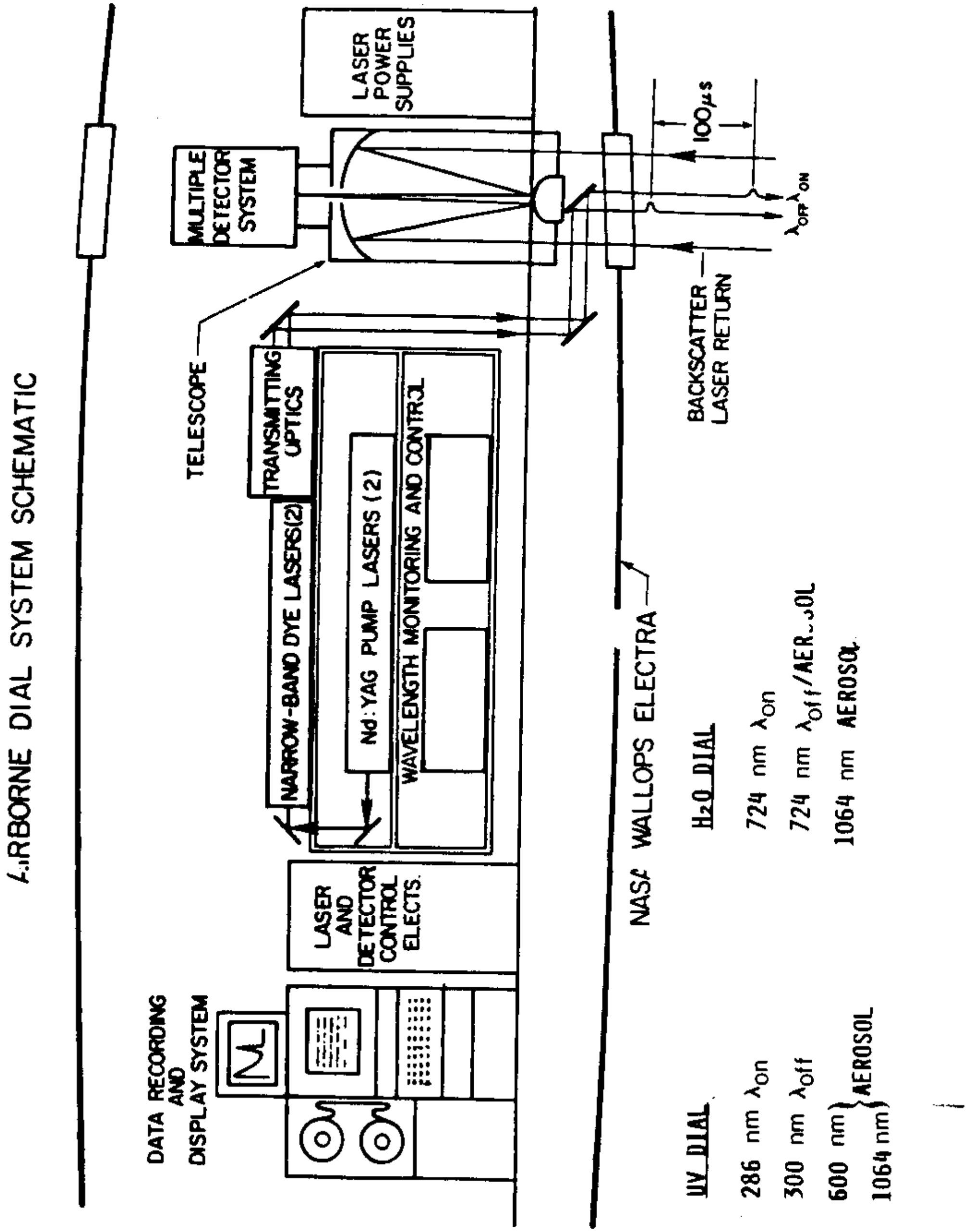
- GKSS (D)
  - UV-VIS-IR DIAL
- NPL (UK)
  - UV-VIS-IR DIAL
- NASA Langley (USA)
  - UV-VIS DIAL
  - Aerosol LIDAR
- DFLR (D)
  - Aerosol LIDAR
  - DIAL for water vapour
- LUND (S)
  - UV-VIS DIAL
- NOAA (USA)
  - Wind Doppler LIDAR
- CNRS (F)
  - Ozone DIAL
  - Fluorescence LIDAR
- IFA - Rome (I)
  - Aerosol LIDAR
- IROE - Florence (I)
  - Ozone DIAL
  - Aerosol LIDAR
- ENEL-CISE (I)
  - UV-VIS-IR DIAL
  - Wind Doppler LIDAR

APPLICATIONS OF NASA LANGLEY AIRBORNE DIAL SYSTEM

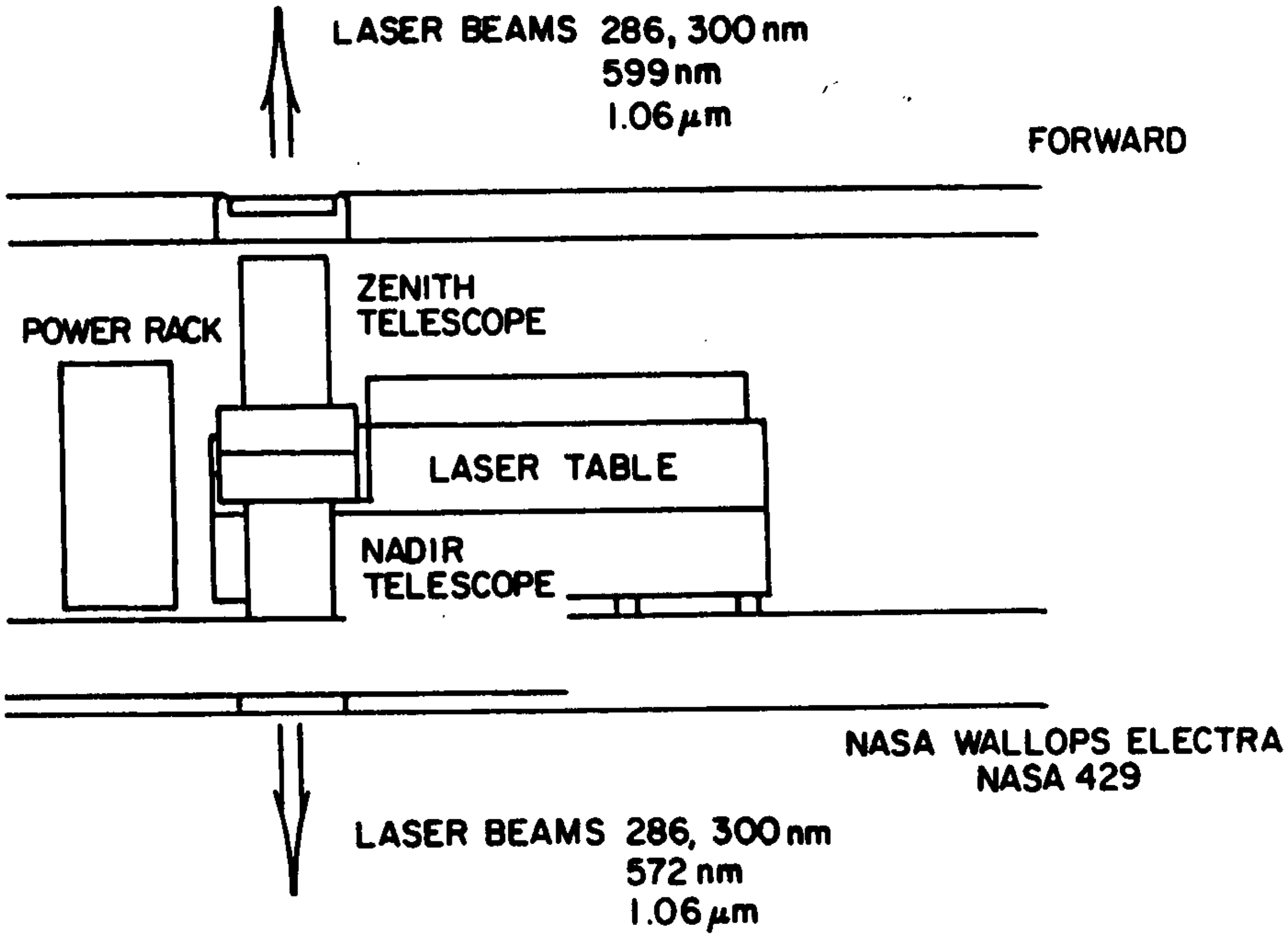
	MEASUREMENTS	INTEREST
GAS SPECIES:	O_3	- NATURAL VERSUS ANTHROPOGENIC SOURCES OF O_3
	H_2O	- METEOROLOGY AND TROP.-STRAT. EXCHANGE
	SO_2	- DISPERSION AND SULFATE CONVERSION IN PLUMES
	NO_2	- SMOG CHEMISTRY AND O_3 PRODUCTION
AEROSOLS:	DISTRIBUTION	- MIXING HT. VARIABILITY AND TROP. DYNAMICS
	COARSE SIZE DIST.	- AEROSOL GROWTH AND DISPERSION PROCESSES
	REL. NUMBER DENSITY	- AEROSOL PRODUCTION AND TRANSPORT
METEOROLOGICAL PARAMETERS:	TEMPERATURE (H_2O OR O_2 DIAL)	- MESOSCALE WEATHER PHENOMENA AND TROPOPAUSE HT DEFINITION
	PRESSURF (O_2 DIAL)	- WEATHER PREDICTION AND WIND DETER.

NASA Airborne DIAL System Characteristics

Transmitter	
Laser system:	Two Nd:YAG pumped-dye lasers
Pulse separation:	100 μs
Nd:YAG pulse energy:	350 mJ at 532 nm
Pulse duration:	15 ns
Repetition rate:	10 Hz
Dye Laser:	Two Jobin-Yvon model HP-HR
Dye output energy:	63 mJ at 720 nm
	47 mJ near 300 nm
Laser Linewidth:	$<0.4\ cm^{-1}$ at 300 nm
	$<0.04\ cm^{-1}$ at 720 nm
Receiver	
Telescope area:	$0.086\ m^2$
Receiver efficiency:	28% at 300 nm
	29% at 720 nm
Detector type:	Photomultiplier
Detector quantum efficiency:	29% at 300 nm
	4.8% at 720 nm
Receiver field of view:	2 mrad



AIRBORNE DIAL SYSTEM SCHEMATIC



NASA
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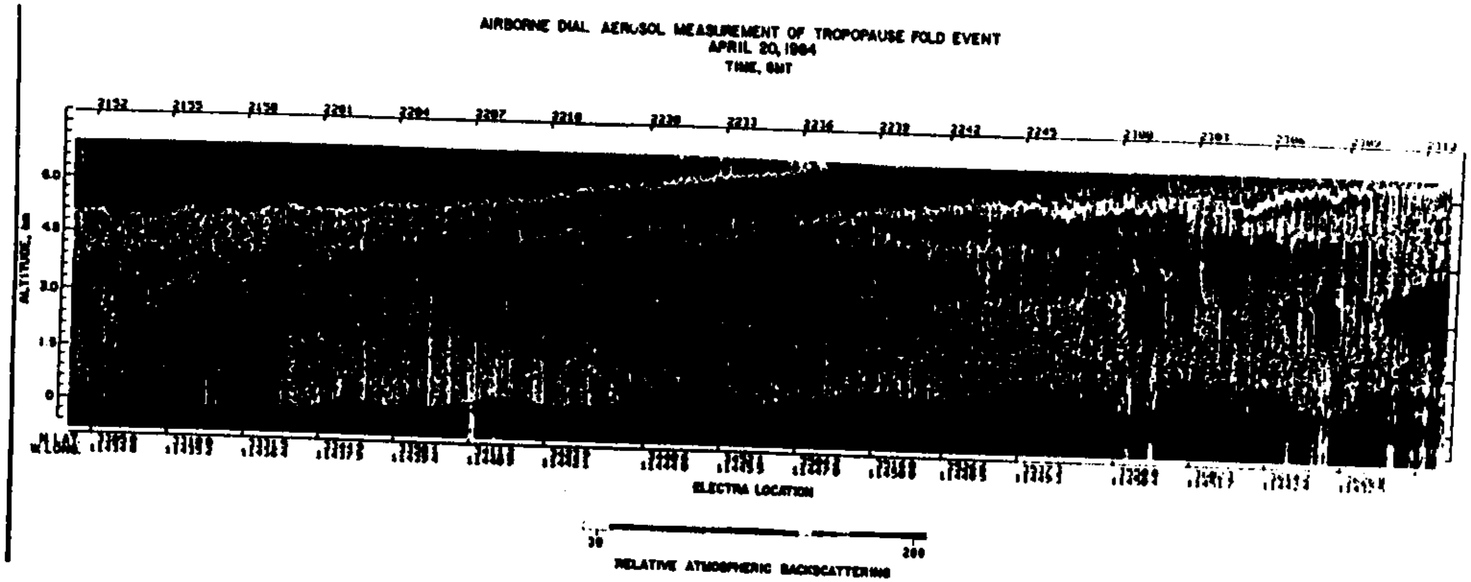

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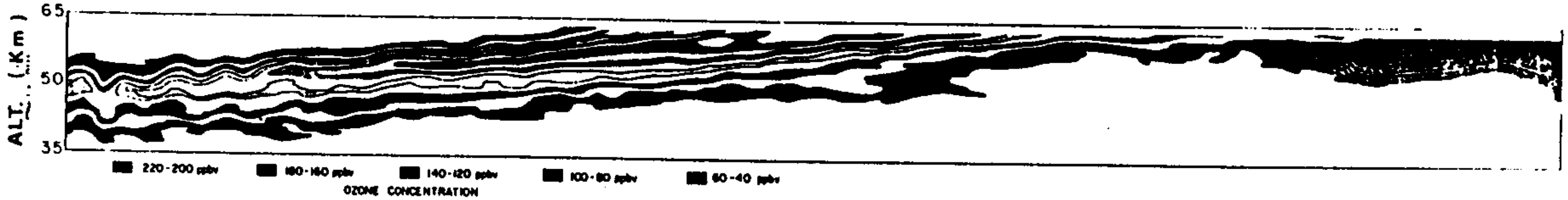
AIRBORNE DIAL O_3 ISOPLETHS

TROPOPAUSE FOLD EXPERIMENT, APRIL 20, 1984



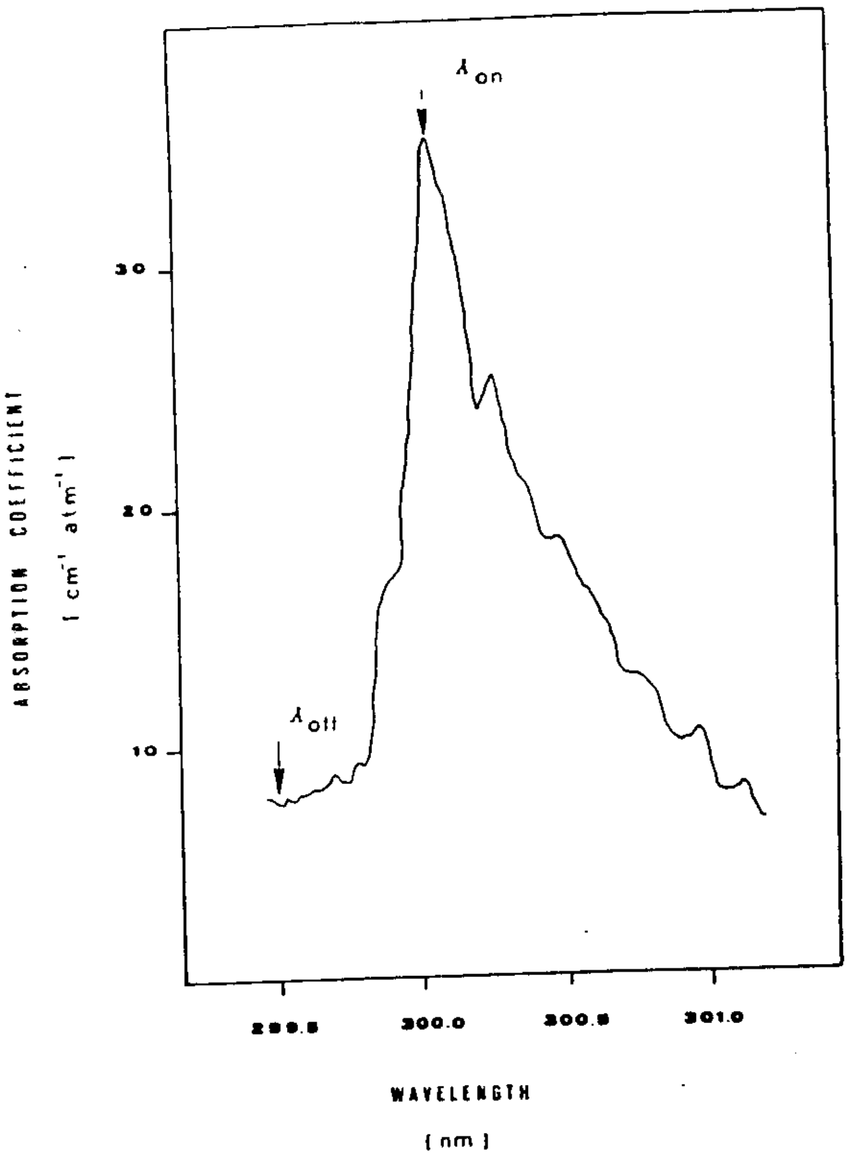
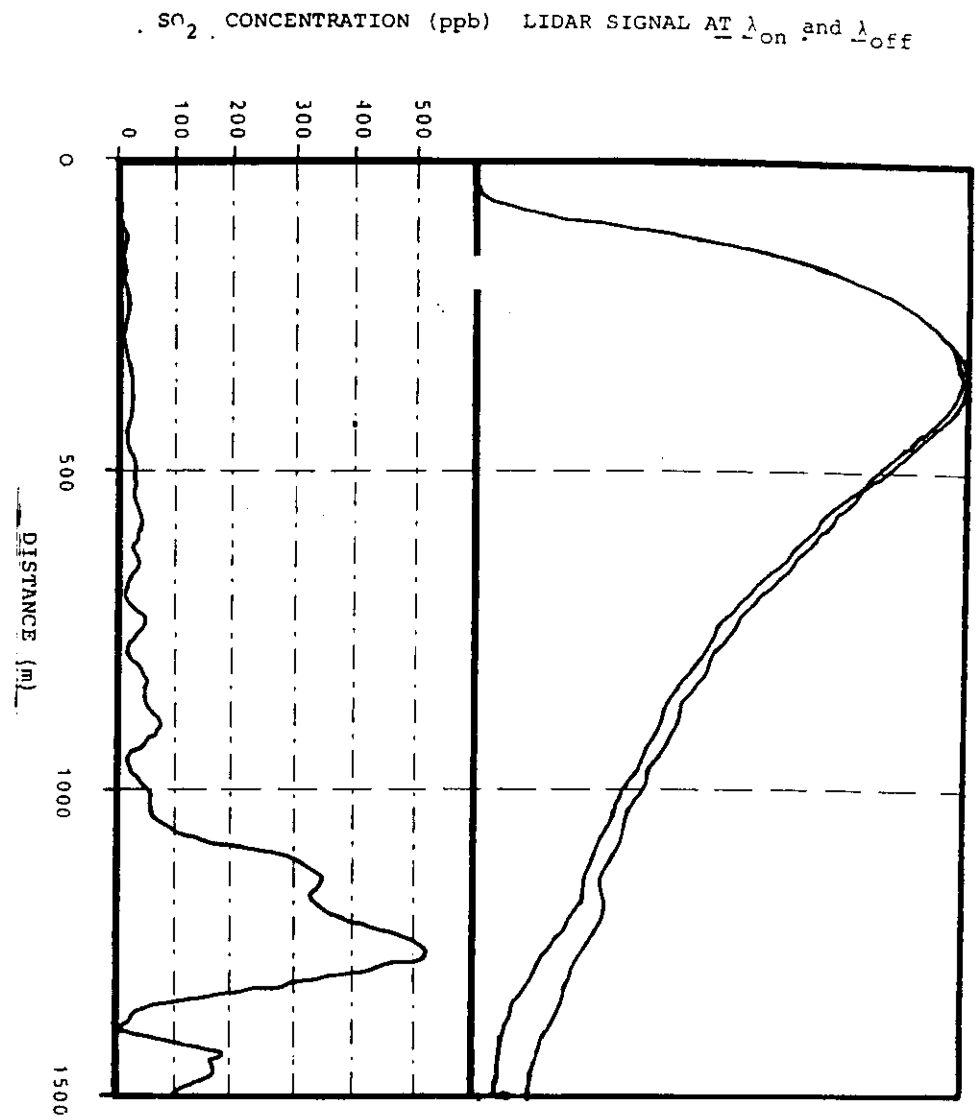


Fig. 1



DIAL detection of a plume from a power plant.

The UV-DIAL system utilizes a doubled dye laser pumped by the 2nd harmonic of a ND-YAG laser with 20 Hz repetition rate.

The emission at λ_{ON} and λ_{OFF} is changed shot by shot by means of a device that inserts a prism in the dye laser oscillator cavity; in this way, the laser beam is deflected on the grating of the laser cavity that selects the wavelength.

The laser beam is coaxially transmitted by means of steering optics to the telescope. This can rotate over a solid angle of 2π with a precision of 0.1° in zenith and 0.25° in azimuth.

The optical signal is detected by a photomultiplier, whose gain is modulated in time with a quadratic law. In this way, the dynamic of the DIAL signals is greatly reduced with improvement of precision in A/D conversion.

The digitazed signal is then transmitted to a DEC VAXStation GPX/II.

Through the electronic control and timing system, the computer is able to make fully automatic measurements.
It is possible to program telescope rotation, laser firing, wavelengths change and other functions.

The software permits measurements over a fan of directions, with real-time data processing.
The results, that is the concentration as a function of distance, are stored on hard disk and are subsequently recalled to get a concentration map using a printer-plotter.

The system is equipped with remote control of laser beam alignment. A TV camera is mounted on the telescope for eye safety and pointing control.
The total time taken for the measurement in one direction, including telescope movement, is about 10-30 seconds.

The system is mounted on a track and is equipped with a power generator of 50 KVA. The set-up time is about 2 hours.

UV DIAL CHARACTERISTICS

TRANSMITTER

LASER SYSTEM	: ND-YAG pumped dye laser
ENERGY OUTPUT	: 300 mJ (at 530 nm)
	10 mJ (at 300 nm)
	10 mJ (at 490 nm)
	30 mJ (at 720 nm)
LASER BANDWIDTH	: 0.1 cm^{-1}
REPETITION RATE	: 20 Hz
PULSE DURATION	: 10 ns

RECEIVER

TELESCOPE AREA	: 0.25 m^2
OPTICS EFFICIENCY	: 20% (SO_2)
FIELD OF VIEW	: 1 mrad
DETECTOR	: Photomultiplier PHILIPS XP-2020Q
DETECTOR SPECIFICATIONS	: 20% quantum efficiency
TRANSIENT RECORDER	: SONY TEKTRONIX 390 AD (10 bit, 10MHz)

PERFORMANCES

RANGE	: up to 3 Km
SENSIBILITY	: 50 ppb (SO_2)
SPATIAL RESOLUTION	: 15 to 200 m
TELESCOPE ANGLE RESOLUTION	: 0.1° in zenith
	0.25° in azimuth

REQUIREMENTS FOR AN ENVIRONMENTAL LIDAR

MULTIPURPOSE SYSTEM

- ABILITY TO DETECT A WIDE CLASS OF POLLUTANTS AND ATMOSPHERIC PARAMETERS (SO_2, NO_2, NO, O_3, CO)

AUTOMATIC MEASUREMENTS

- FULL COMPUTER CONTROL
- MIMIMUM OPERATOR ASSISTANCE
- NO OR REDUCED MAINTENANCE

IMPROVED INSTRUMENTATION

- ALL SOLID STATE TUNABLE LASER
- HIGH DYNAMIC RANGE RECEIVER

INTEGRATION IN A MONITORING NETWORK

- LIDAR STANDARDIZATION
- LIDAR DATA INTEGRATION

DIAL SPECIFICATIONS

TRANSMITTER

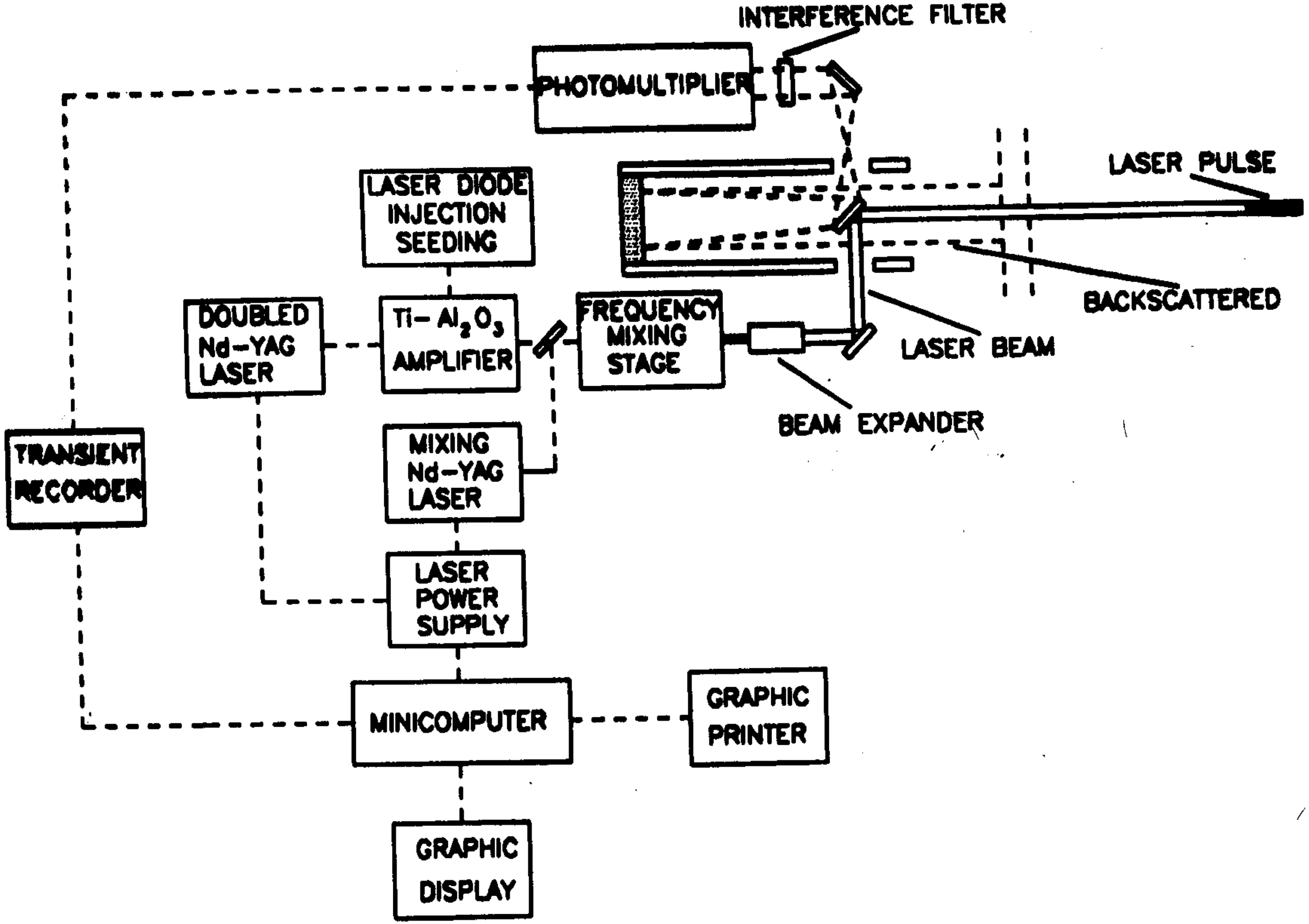
Laser type	Titanium sapphire
Output energy	100 mJ @ 750-850 ı
	≈ 10 mJ in the U\
Tuning range	226 nm - 3 μm
Rep.Rate	20 Hz
Pulse duration	10 ns
Bandwidth	single longitudinal de
Beam Quality	near diffraction lin

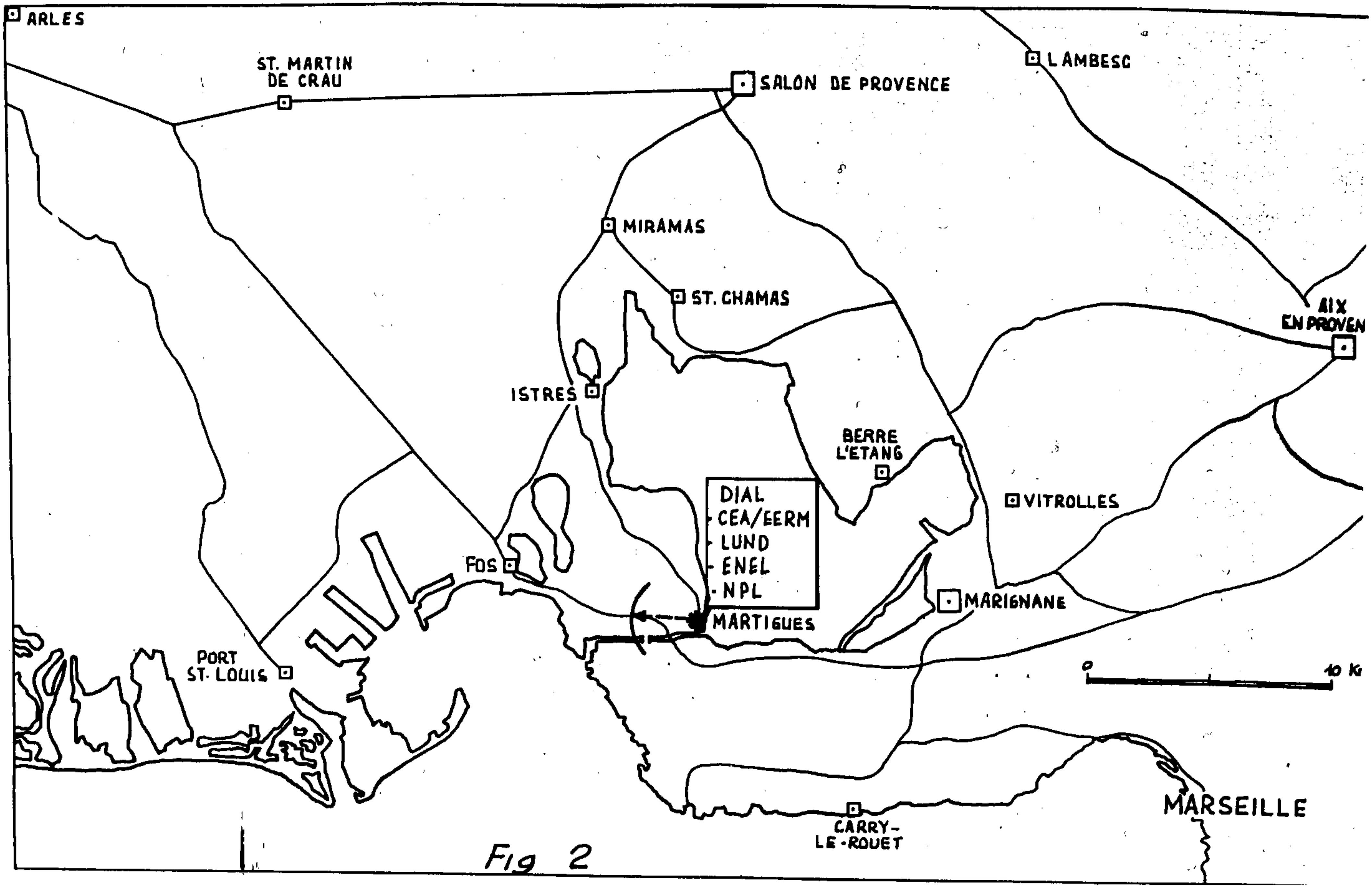
RECEIVER

Telescope	600 mm newtonian
Detectors	2 PMTs with T^2 ga
Digitizer	18 bit, 10 MHz

LASER DESIGN CONCEPTS

REQUIREMENTS	SOLUTIONS
Wide tunability	Titanium sapphire + mixing
High frequency conversion efficiency and high energy output	- good beam profile → graded reflectivity mirrors resonator - short pulse → laser pumping - mixing with a high power Nd:YAG laser
Narrow band	- ring resonator - injection locked regenerative amplifier
Frequency stability	- injection locking with temperature and current controlled laser diodes - mixing with a stable Nd:YAG laser


INTERFERENCE FILTER
PHOTOMULTIPLIER
LASER PULSE
LASER DIODE INJECTION SEEDING
BACKSCATTERED
DOUBLED Nd-YAG LASER
Ti-Al_2O_3 AMPLIFIER
FREQUENCY MIXING STAGE
LASER BEAM
BEAM EXPANDER
TRANSIENT RECORDER
MIXING Nd-YAG LASER
LASER POWER SUPPLY
MINICOMPUTER
GRAPHIC PRINTER
GRAPHIC DISPLAY


ARLES
ST. MARTIN
DE CRAU
SALON DE PROVENCE
LAMBESC
MIRAMAS
ST. CHAMAS
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LE-ROUET

Fig 2

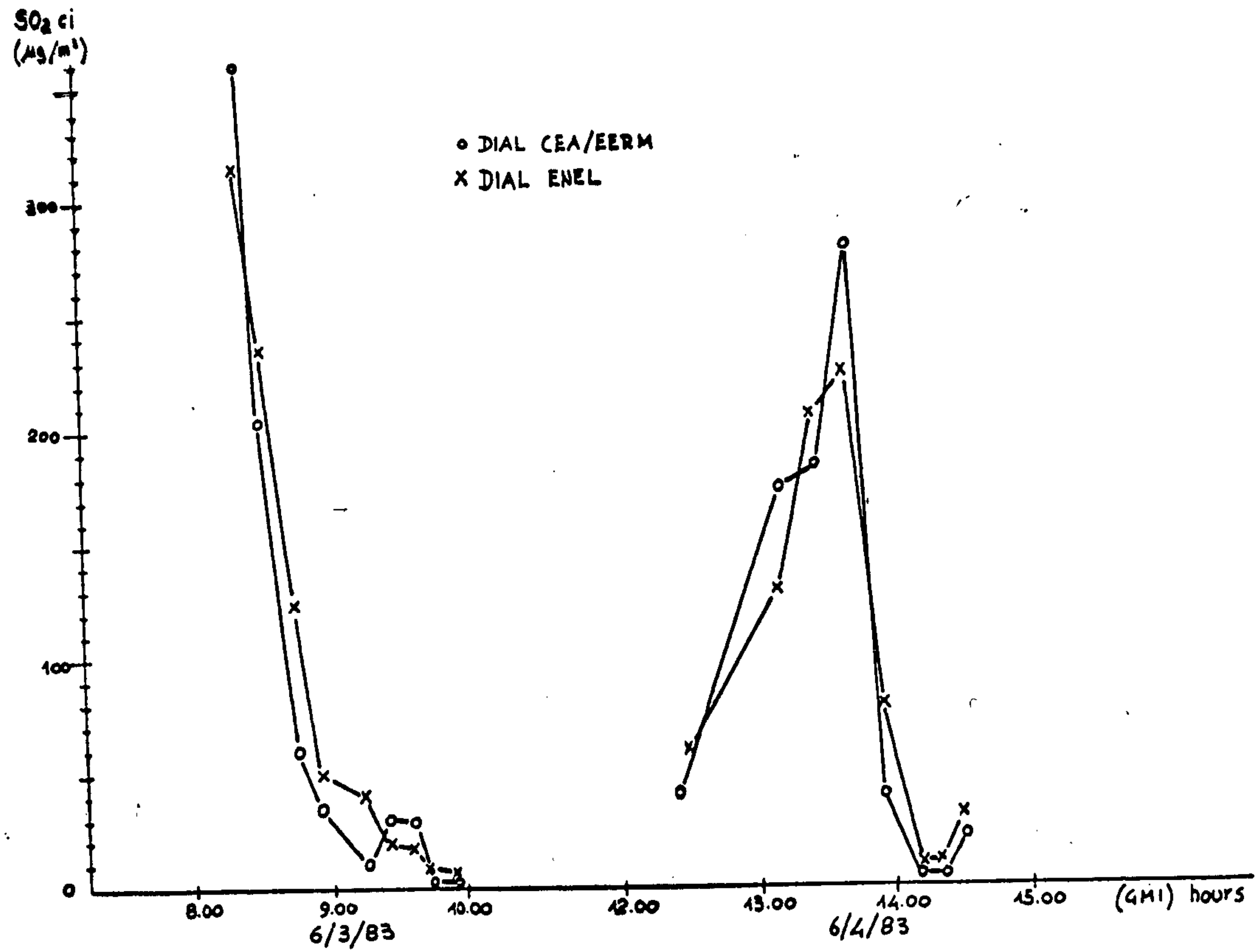

SO_2 ci
(μg/m³)
300
200
100
0
o DIAL CEA/EERM
x DIAL ENEL
8.00
9.00
10.00
12.00
13.00
14.00
15.00
(GMT) hours
6/3/83
6/4/83

Fig. 2

Since 1982, this DIAL system has been used during experimental campaigns in different sites (industrial and/or urban areas) to track plumes near the Power Plants, monitor SO_2 over large areas and also measure gas emissions from soil and fumaroles in volcanic areas.

In order to fulfill the requirements of every kind of campaign, the SW was developed to comply with the following requirements:

- only one type of data processing to satisfy the different experimental situations;
- real-time definitive concentration data results;
- estimate of experimental error on concentration measurement linked with its value.

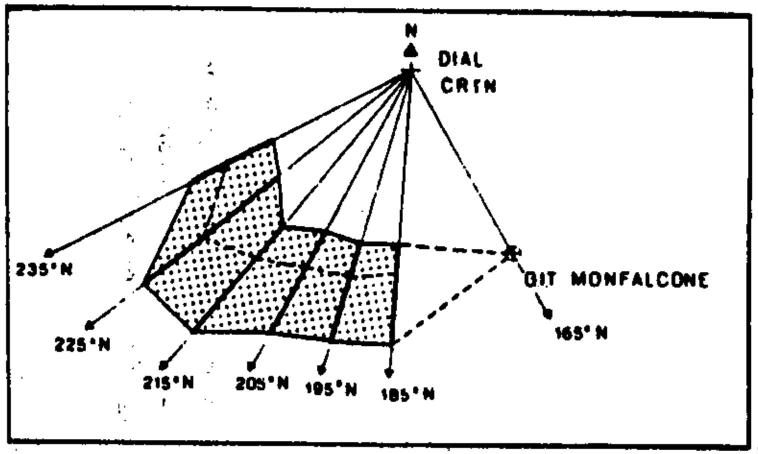
EXPERIMENTAL CAMPAIGNS PERFORMED BY THE UV-DIAL SYSTEM (FROM 1983 UP TO NOVEMBER 1989)

TYPE OF MEASUREMENTS	HOURS OF WORK
Power Plant Plume tracking (for differnt aims) MONFALCONE, SANTA GILLA	1500
Refinery FOS-BERRE CEC 1983 CAMPAIGN	200
Industrial area SULCIS, VADO LIGURE FOS-BERRE CEC 1983 CAMPAIGN	700
Urban area ROME	400
Other (volcanic, geothermal area) VULCANO ISLAND	200

MONFALCONE 19-6-85

6.22 (185°N); 6.33 (195°N); 6.47 (205°N);

6.57 (215°N); 7.09 (225°N); 7.35 (235°N).



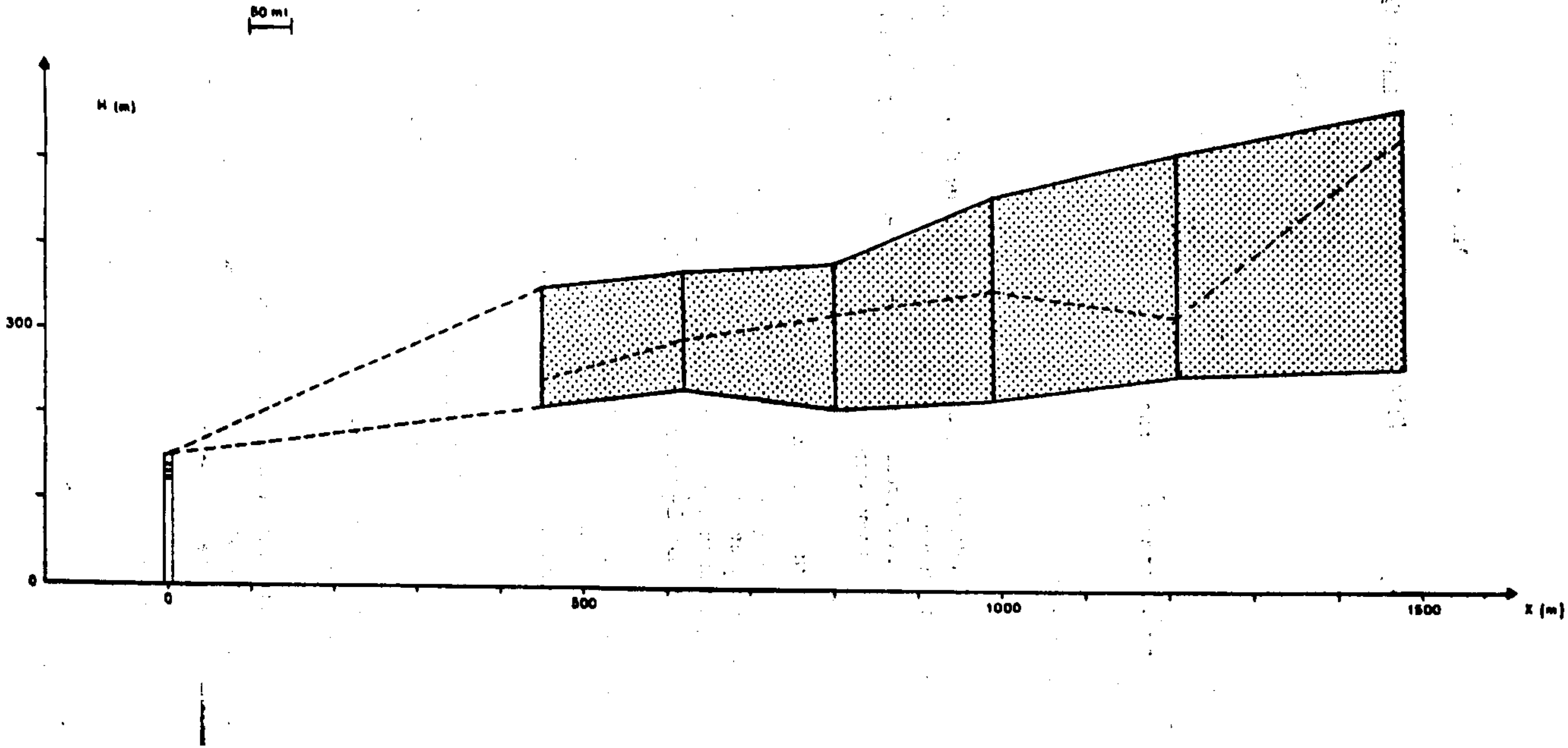


Fig. 3

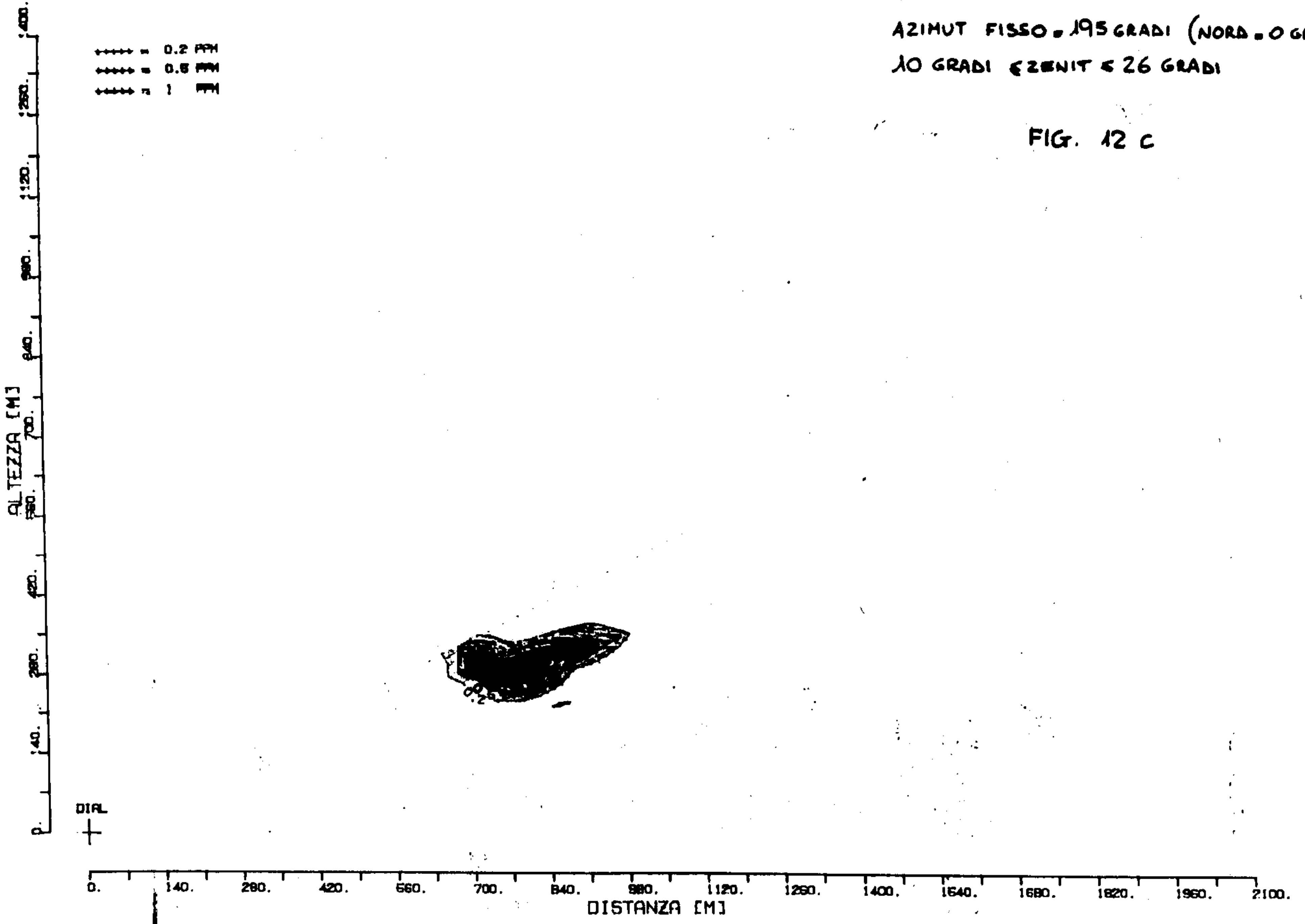
MONFALCONE 19-6-85

6:33

AZIMUT FISSO = 195 GRADI (NORD = 0 GRADI)

10 GRADI ≤ ZENIT ≤ 26 GRADI

FIG. 12 c



Monfalcone 19-6-85
6:47
AZIMUT FISSO = 205 GRADI (NORD = 0 GRA
14 GRADI ≤ ZENIT ≤ 30 GRADI

FIG. 12 d

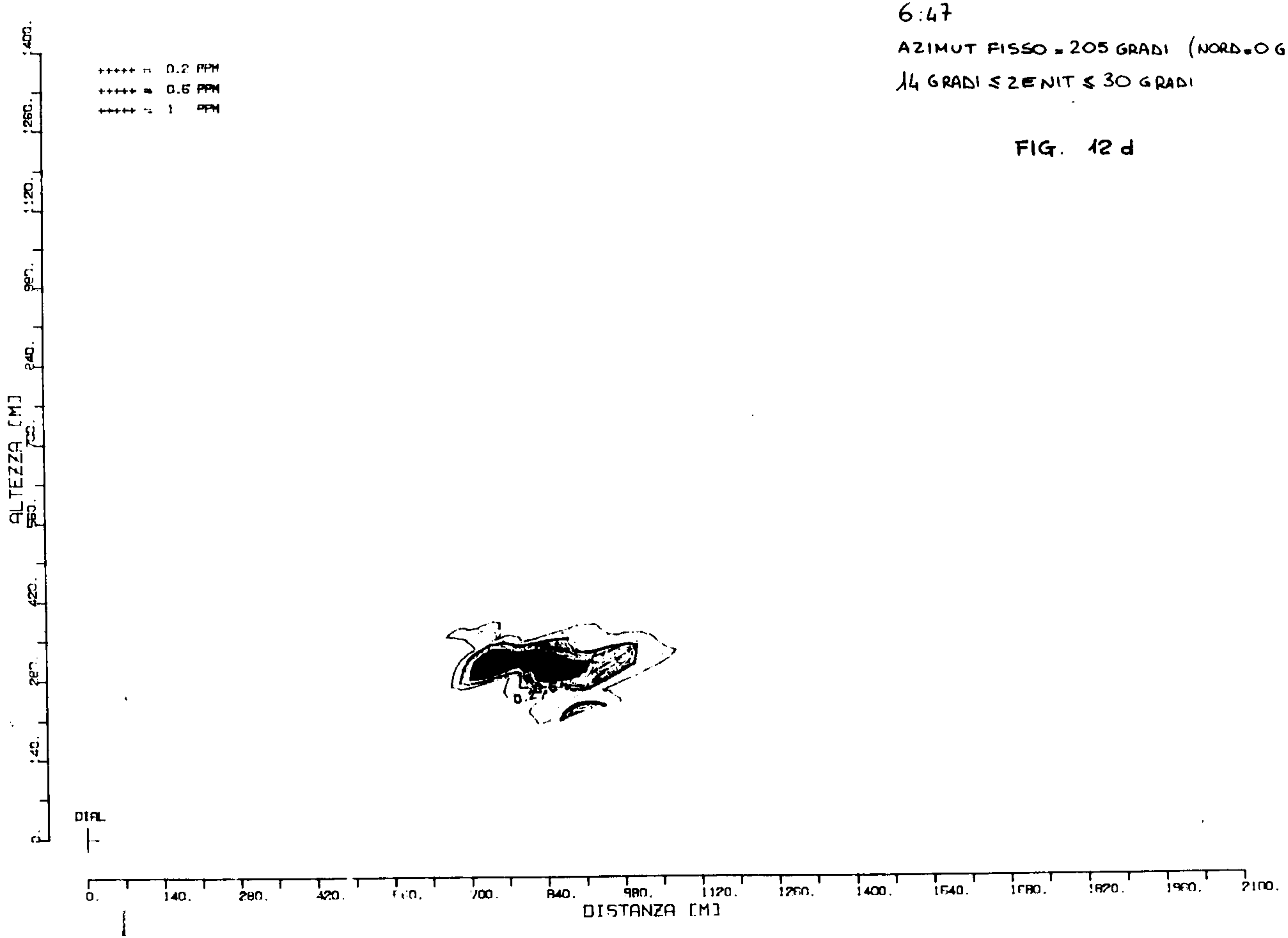


Fig. 7

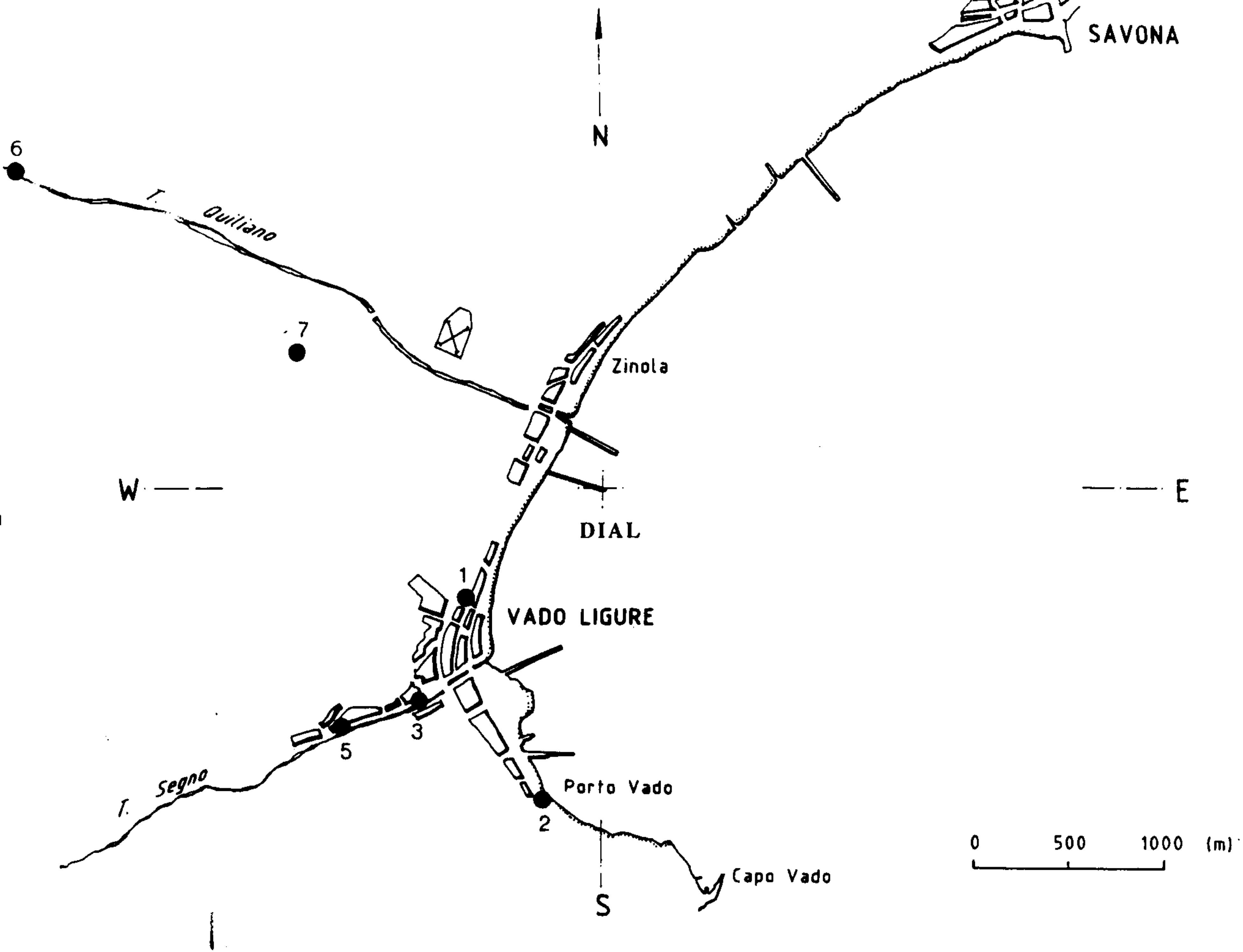
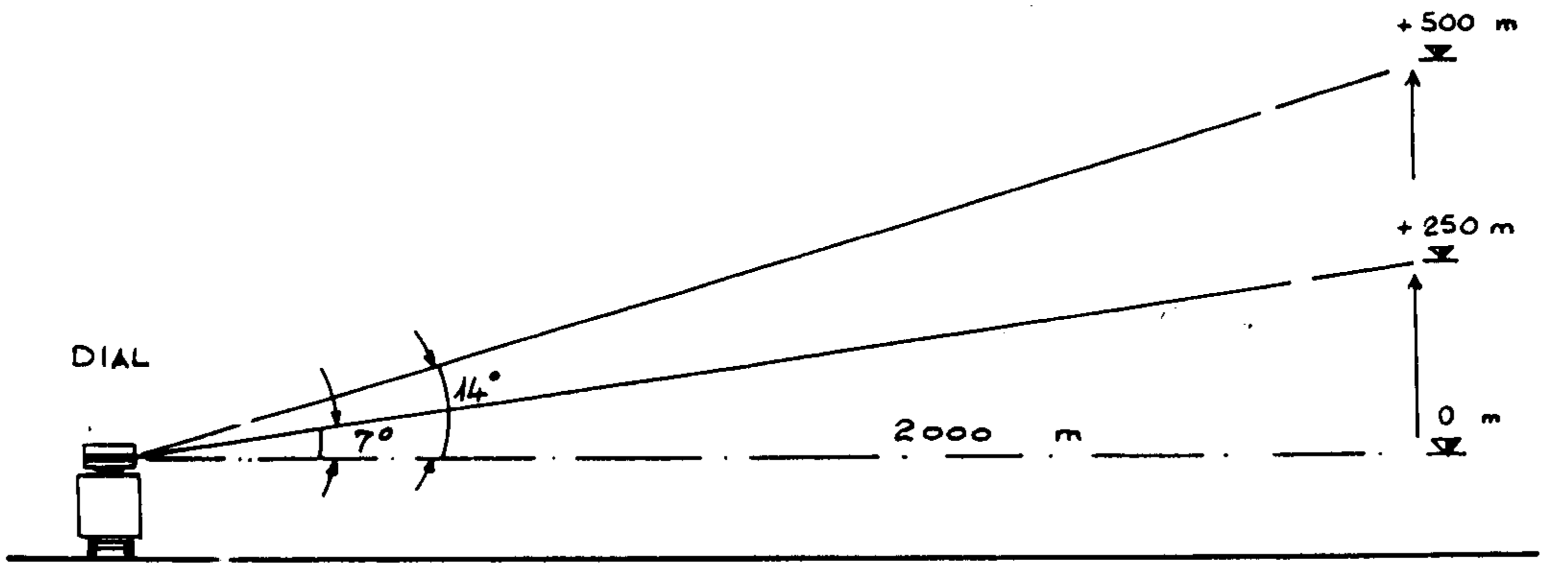

SAVONA
N
6
T. Quiliano
7
Zinola
W
E
DIAL
1
VADO LIGURE
3
5
T. Segno
Porto Vado
2
0 500 1000 (m)
Capo Vado
S

Fig. 8



VADO L. (WHARF)

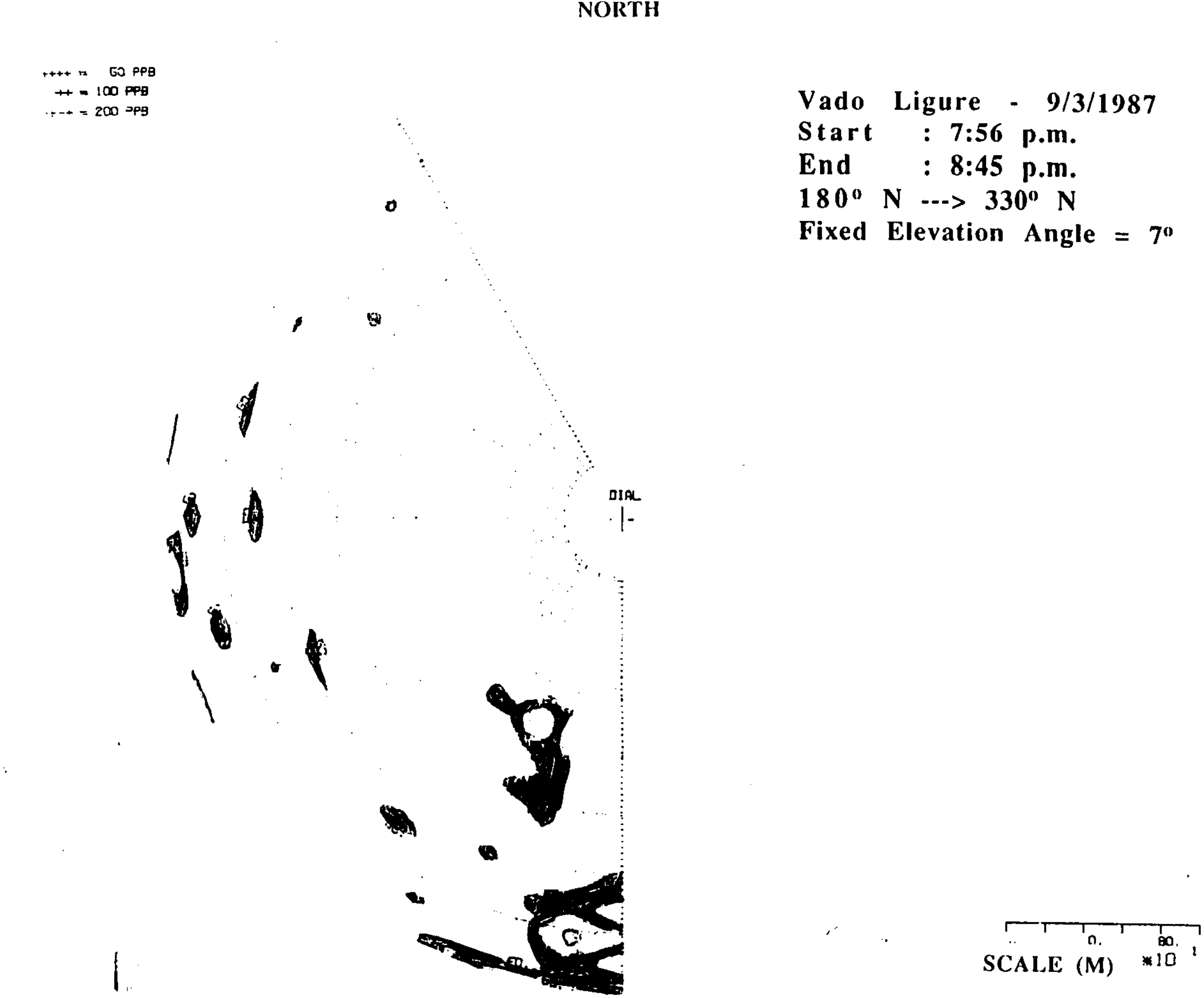

NORTH
++++ = 60 PPB
++ = 100 PPB
-+-+ = 200 PPB
Vado Ligure - 9/3/1987
Start : 7:56 p.m.
End : 8:45 p.m.
180° N ---> 330° N
Fixed Elevation Angle = 7°
DIAL
0.
80.
SCALE (M)
*10

Fig. 9.a

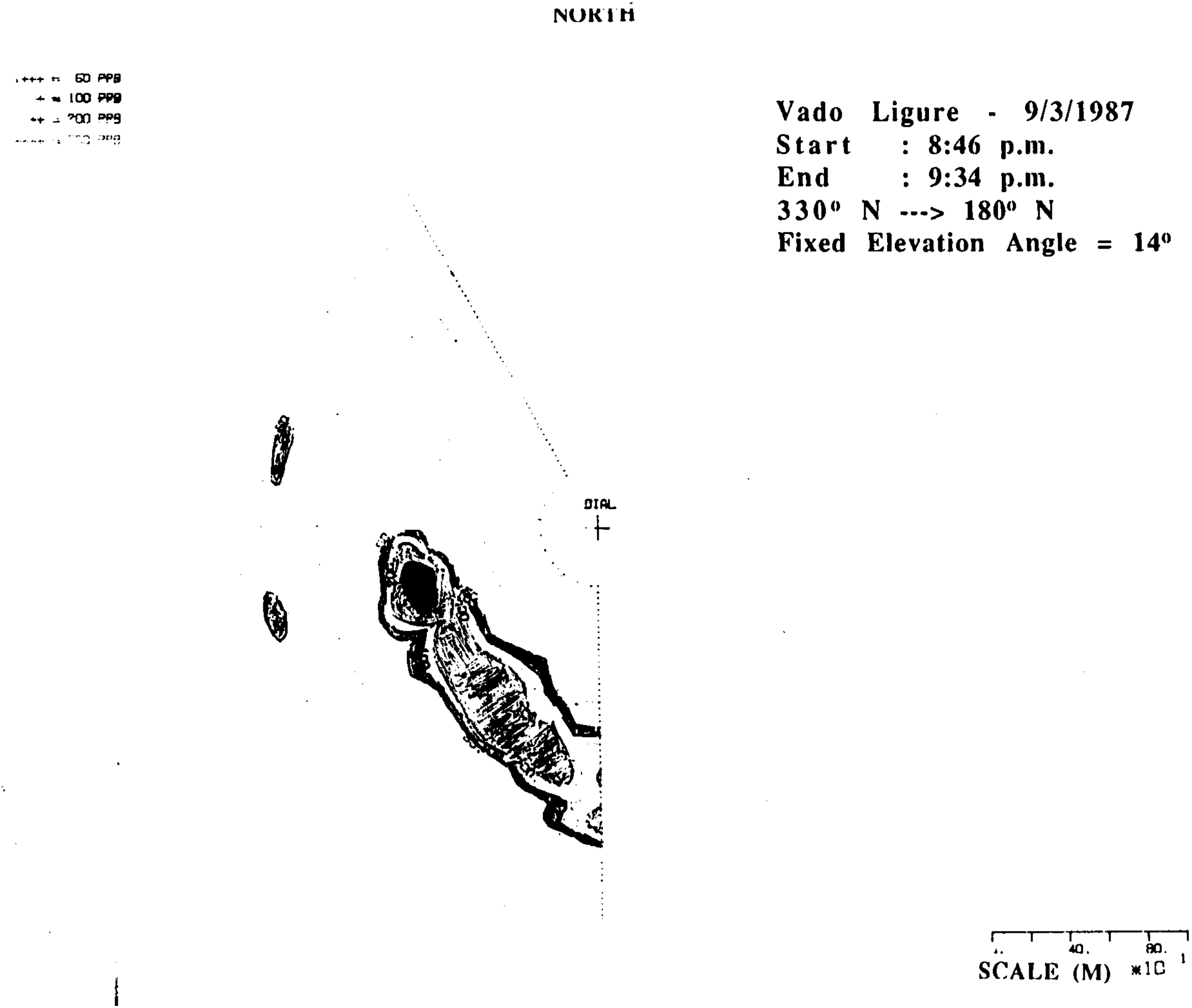
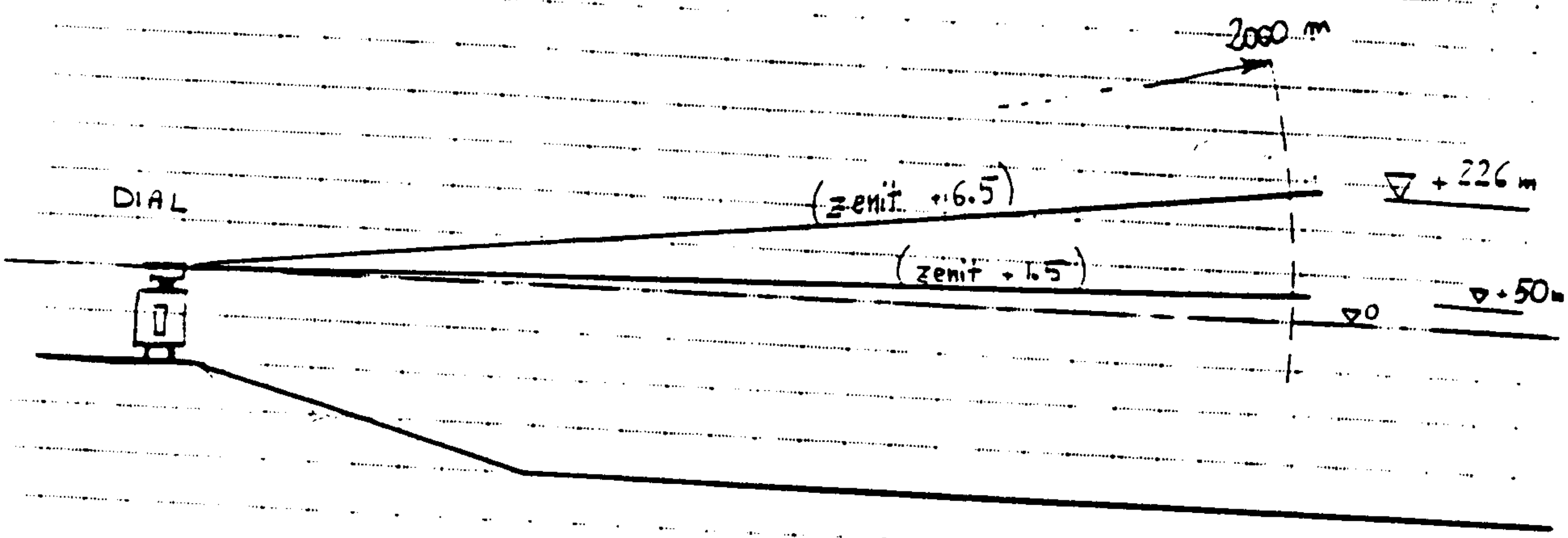
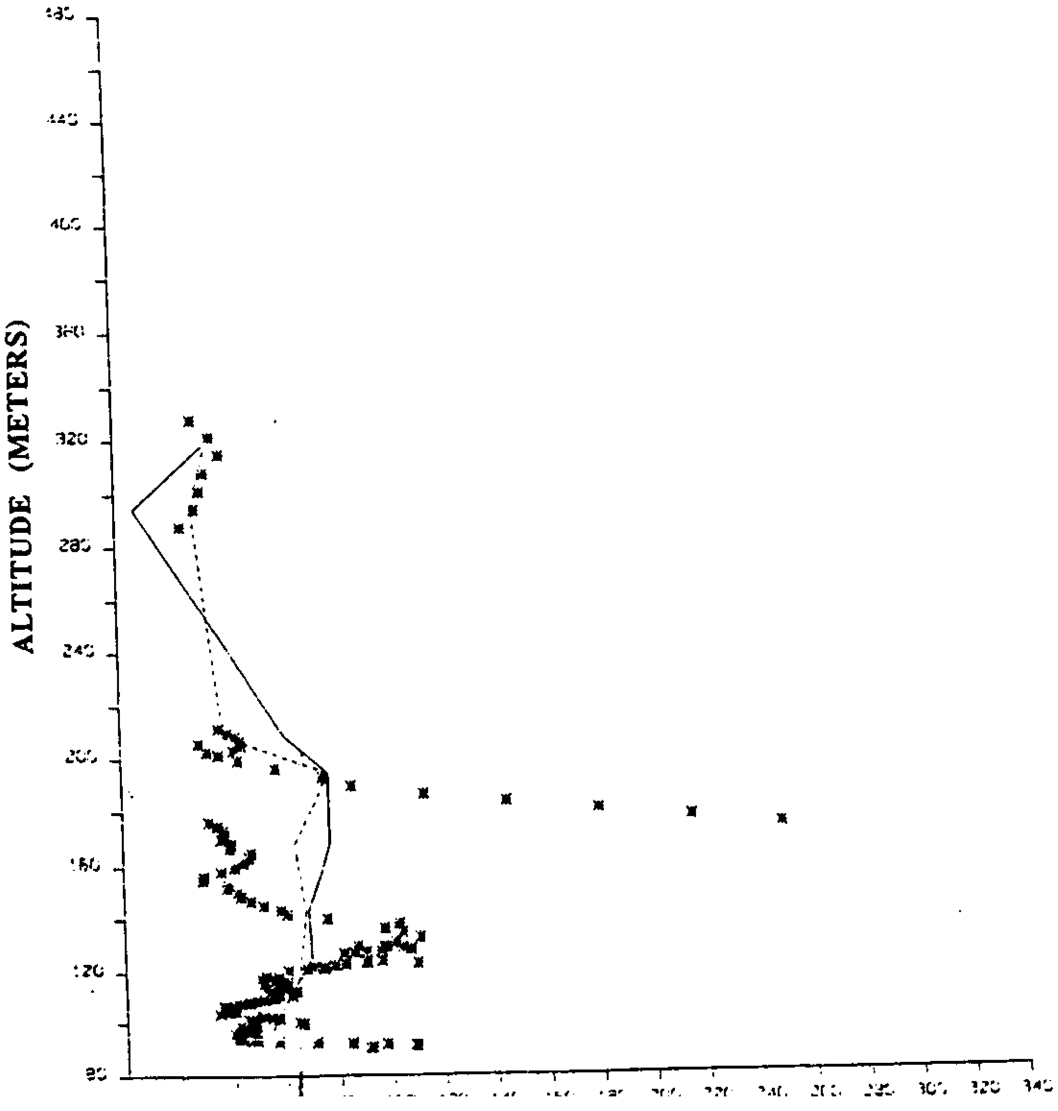

NORTH
++++ = 60 PPB
+ = 100 PPB
++ = 200 PPB
Vado Ligure - 9/3/1987
Start : 8:46 p.m.
End : 9:34 p.m.
330° N ---> 180° N
Fixed Elevation Angle = 14°
DIAL
40.
80.
SCALE (M) *10 1

Fig. 9.b



DIAL
2000 m
(zenit +6.5)
(zenit +1.5)
+226 m
+50m
0

Rome (Gianicolo Hill)
14/1/1987
Start : 5:45 a.m.
End : 4:44 p.m.



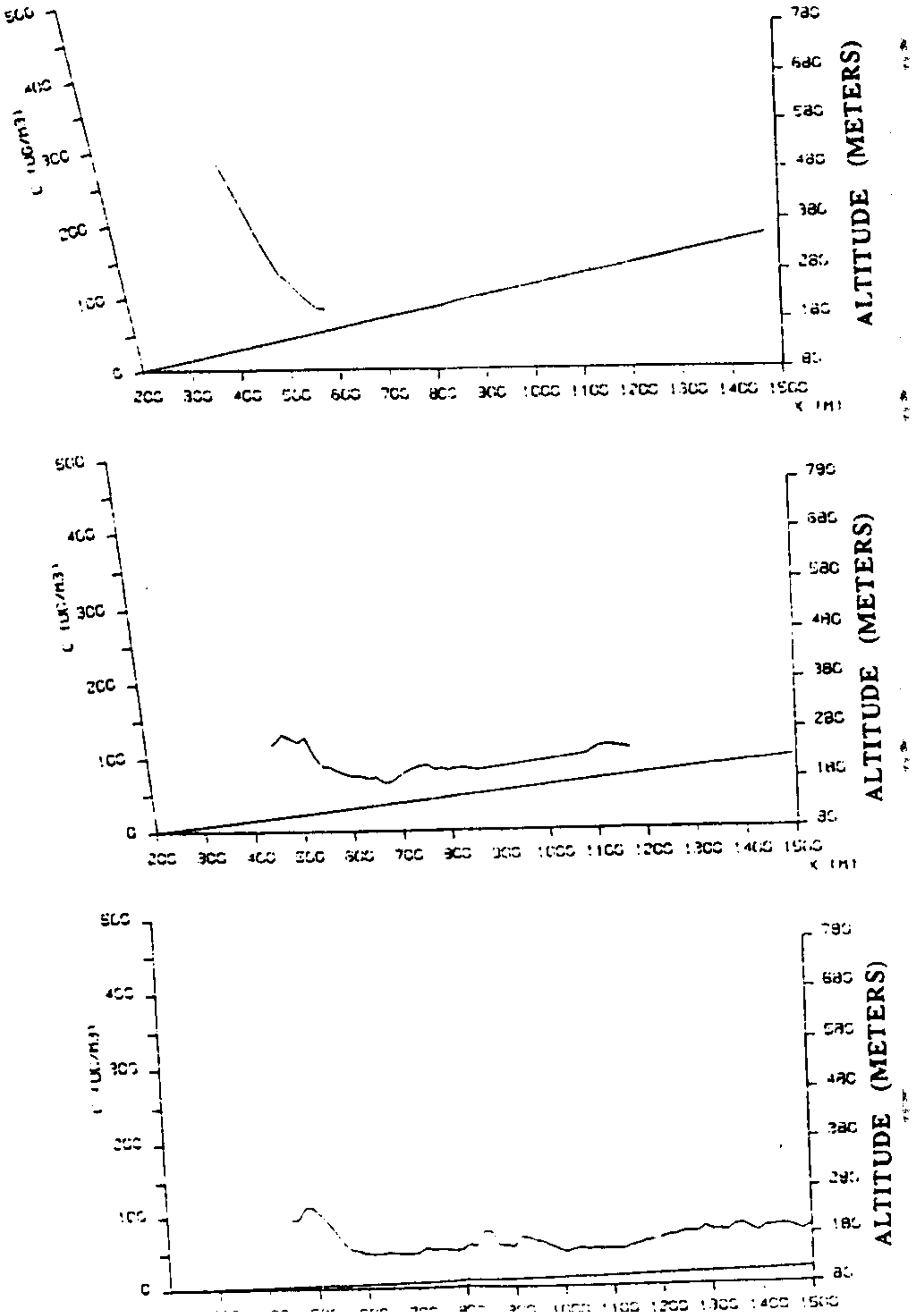
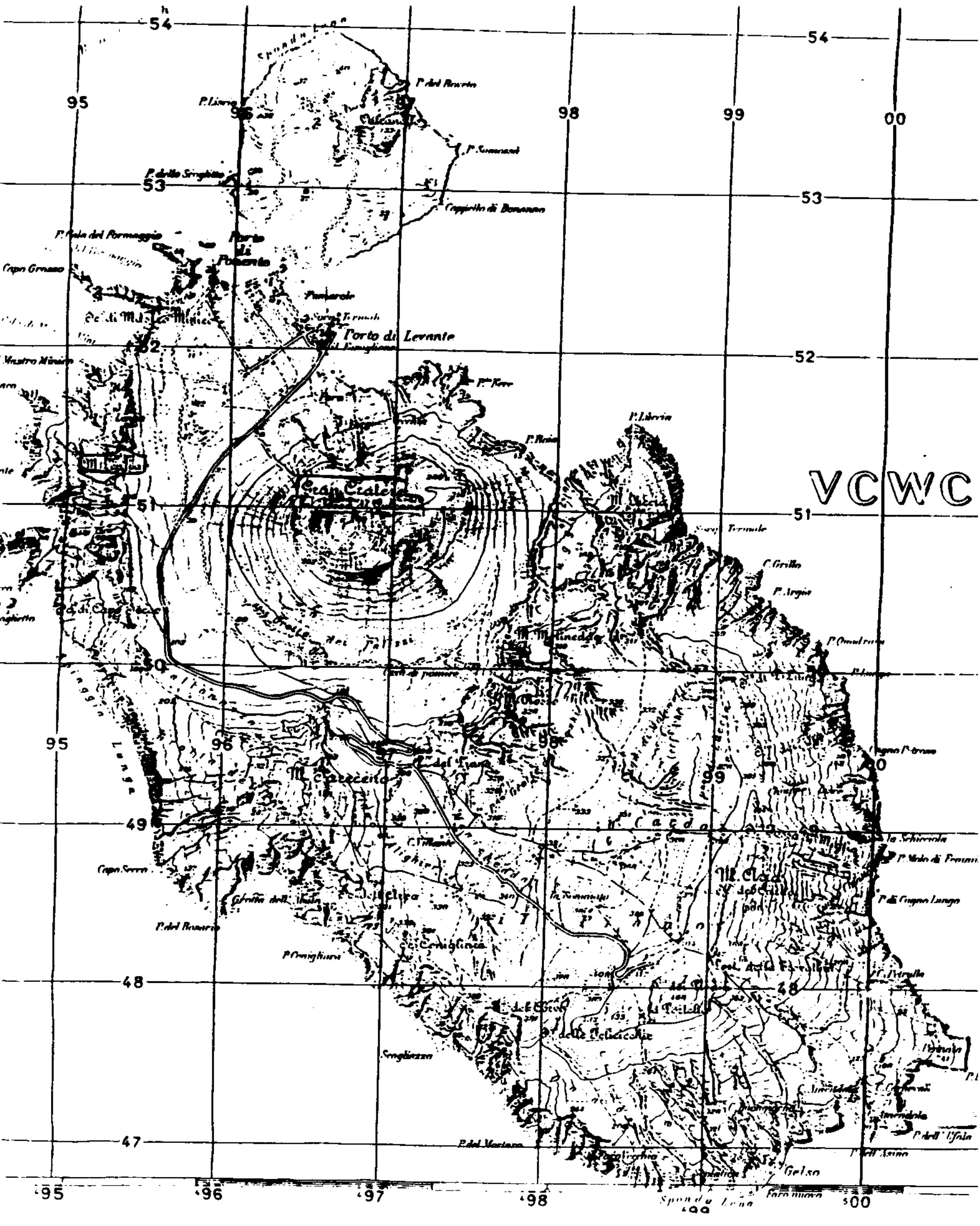


Fig. 10


VCWC
Porto di Levante
Porto di Ponente
P. del Rosario
P. Samuel
Coppolitto di Bonanno
P. delle Sirighitte
Capo Grosso
Punturale
P. Roia
P. Libreria
C. Grillo
P. Argio
La Schicciola
P. di Capo Lungo
Capo Secco
P. del Rosario
Scoglietto
P. del Monaco
P. dell' Ufala
Gelso
Faro nuovo
95
96
97
98
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00
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48
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50
51
52
53
54

GRAPH PARAM FILE: VUL89025GR DATA FILE: VUL89025
DIR. RANGE: -88.0 - -52.0 DIST. RANGE: 200.0 - 1500.0 LEVELS #: 6
ACQ. START: 16/11/89 12:59:38 STOP: 16/11/89 13:11:00
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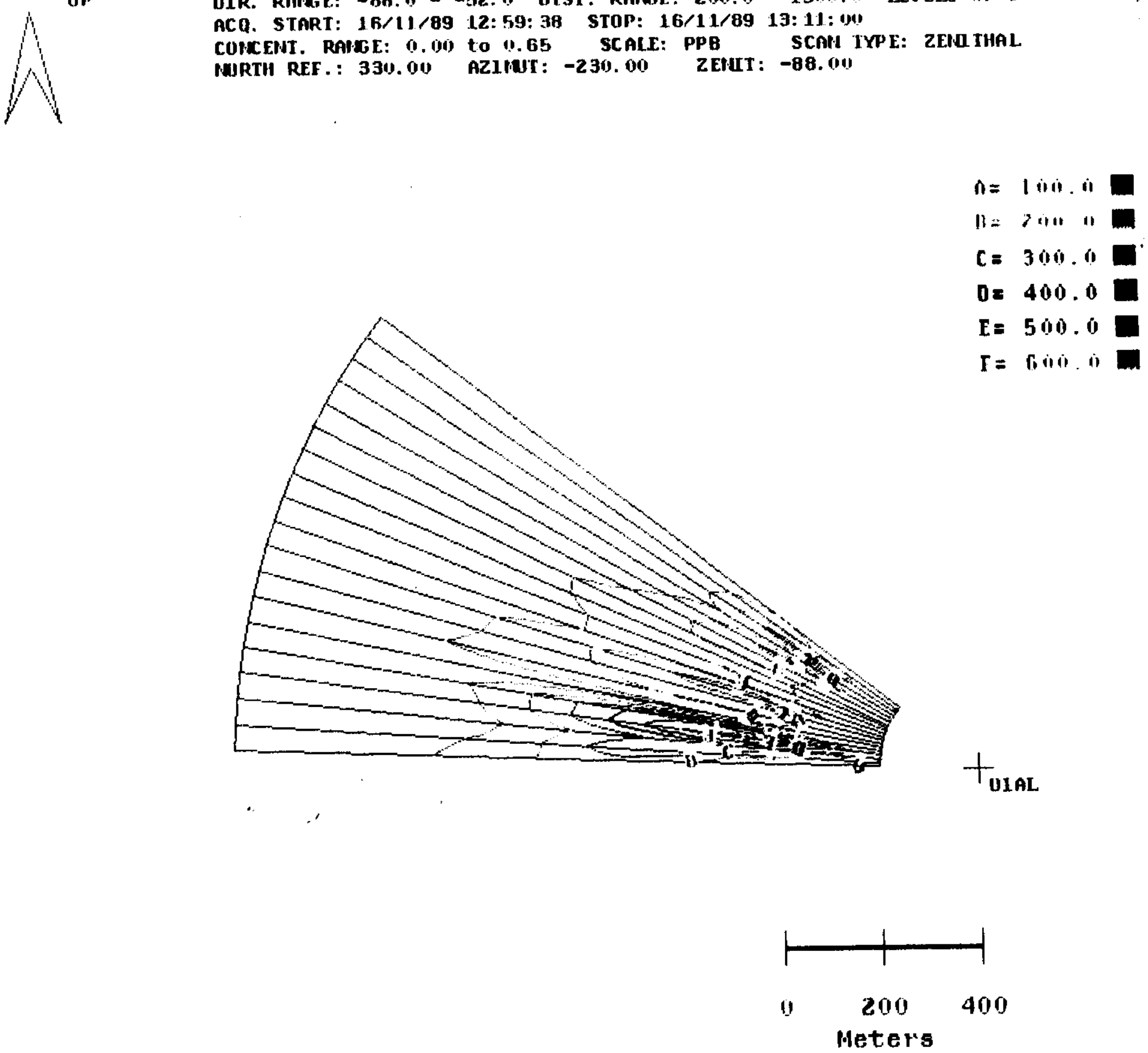
NORTH REF.: 330.00 AZIMUT: -230.00 ZENIT: -88.00



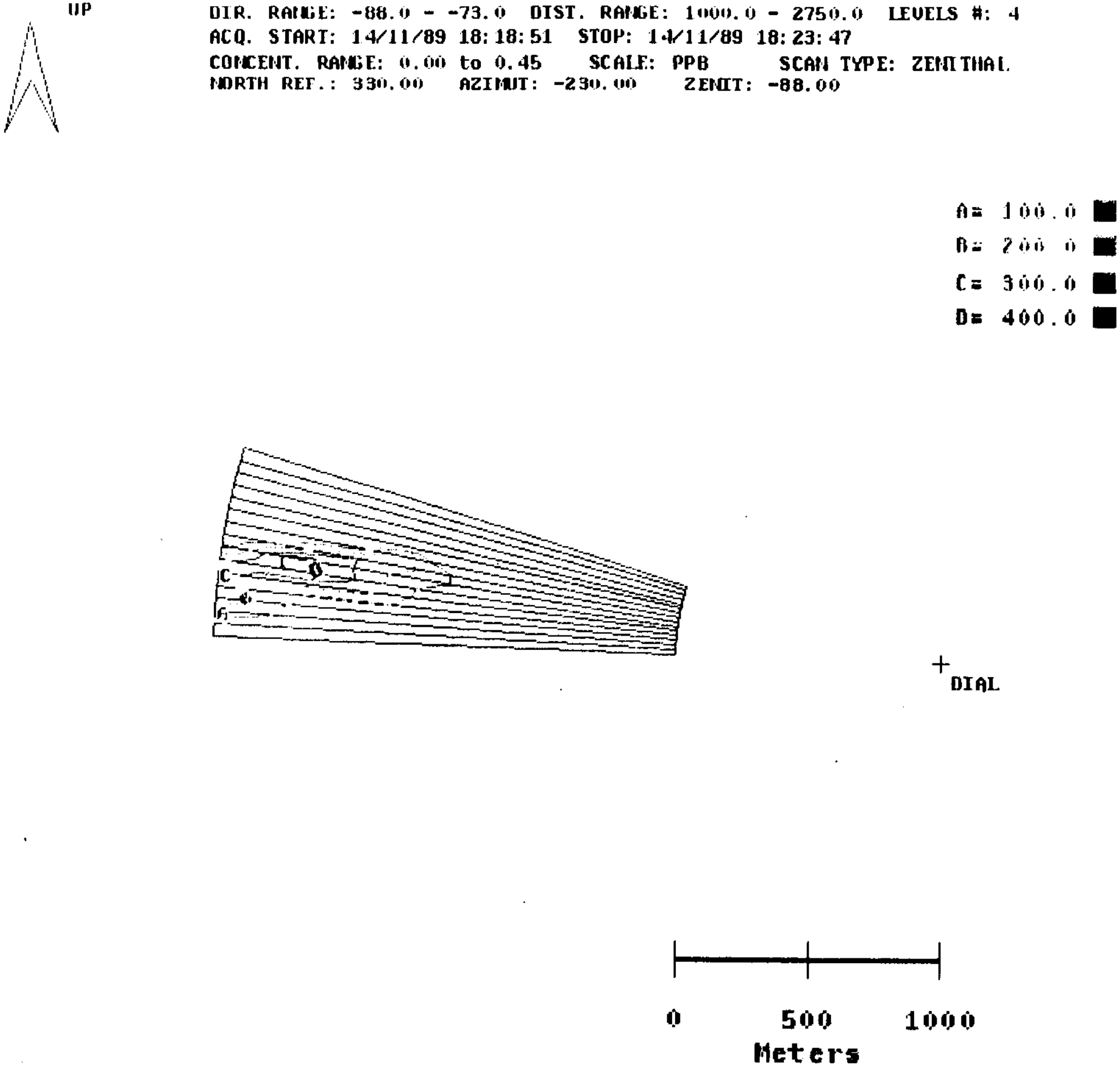
GRAPH PARAM FILE: VUL89007GR DATA FILE: VUL89007

DIR. RANGE: -88.0 - -73.0 DIST. RANGE: 1000.0 - 2750.0 LEVELS #: 4

ACQ. START: 14/11/89 18:18:51 STOP: 14/11/89 18:23:47

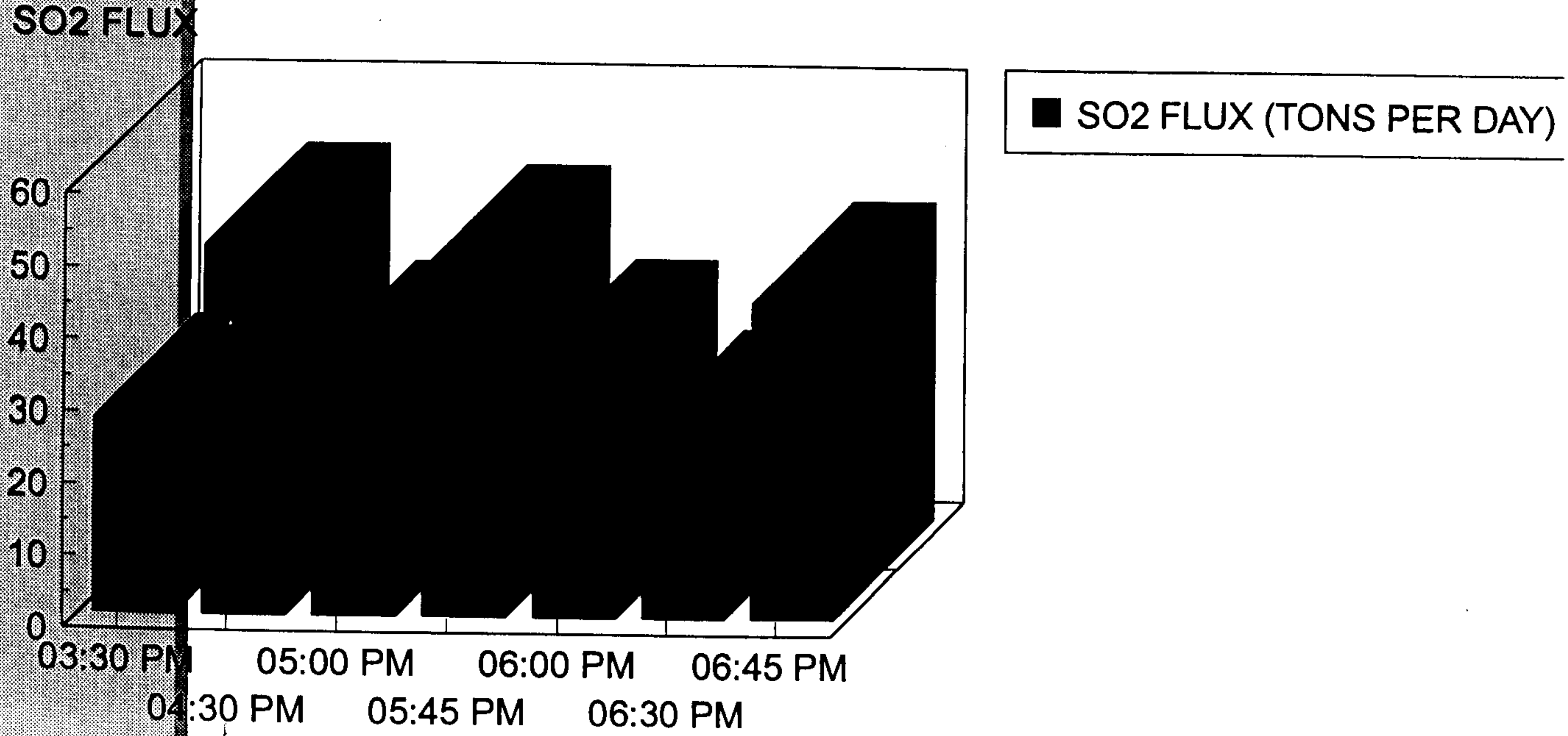
CONCENT. RANGE: 0.00 to 0.45 SCALE: PPB SCAN TYPE: ZENITHAL

NORTH REF.: 330.00 AZIMUT: -230.00 ZENIT: -88.00



Vulcano DIAL Campaign 1989

- Measurements of Sulphur Dioxide Fluxes



DOPPLER WIND LIDAR

System specifications

- maximum range: 20 km
- wind velocity resolution (radial velocity): 1 m/s
- range resolution 300 m

Transmitter

- Laser type: pulsed TEA CO_2 laser
- pulse energy: 2 J
- pulse duration: 3 μs
- repetition rate: 10 Hz
- bandwidth: 300 kHz

Receiver

- telescope aperture: 30 cm
- detector: cooled HgCdTe
- detection type: Heterodyne
- wind evalutation: by frequency analysis of Doppler shifted return signal

ANALYSIS OF THE OILS PRESENT ON THE SEA SURFACE

ANALYSIS OF THE WATER COLUMN

SPECTRAL ANALYSIS + TEMPORAL ANALYSIS