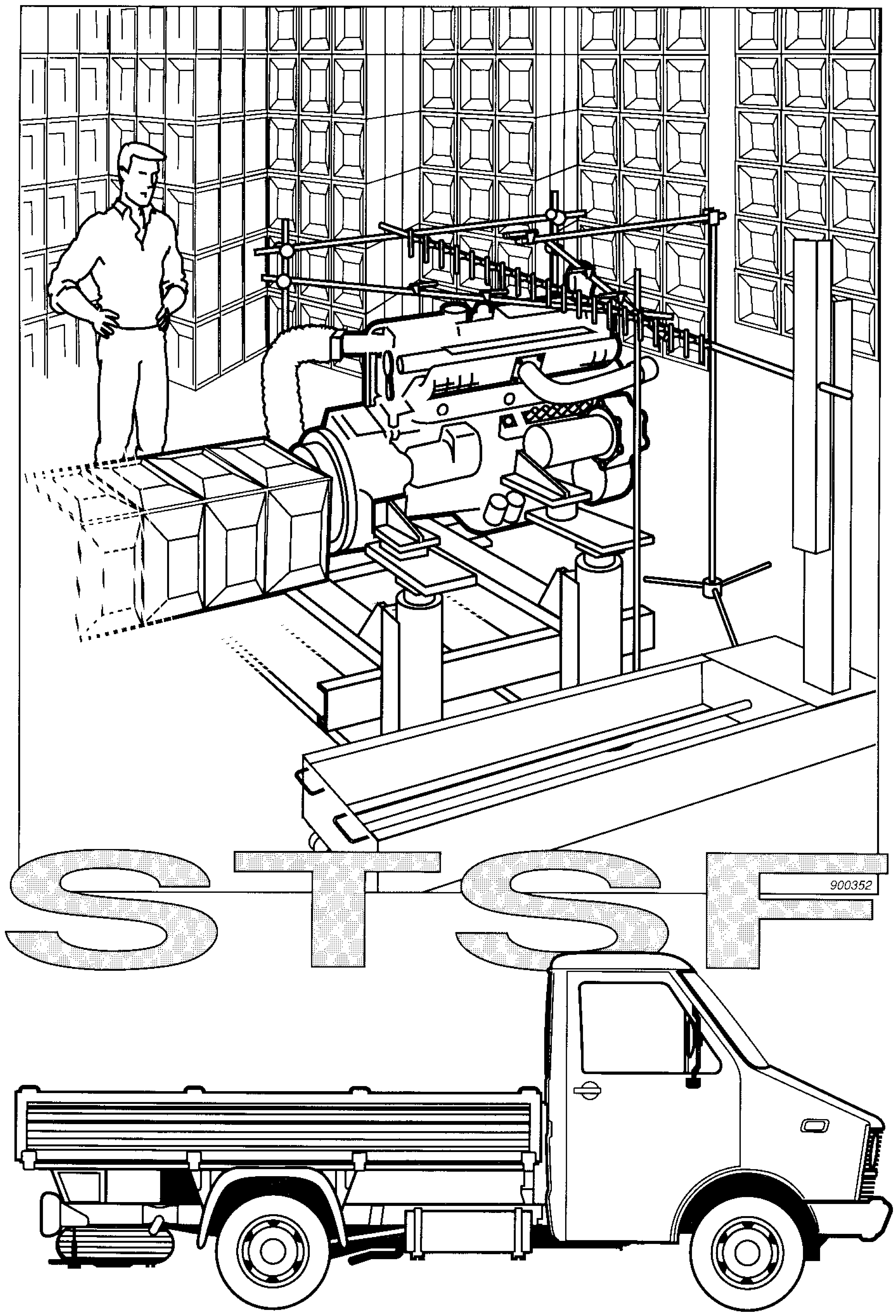
Application Notes

Acoustical testing in the automotive industry using STSF



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Acoustical testing in the automotive industry using STSF

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Introduction

Acoustical testing has been in use by the automotive industry from the beginning, for solving noise problems. The measurement procedures have been refined in the course of time from the simple use of the ear to computer assisted subjective and objective measurements. For example, in objective testing the sound pressure level at a single measurement position is now frequently supplemented by a sound power determination and lead wrapping techniques have been largely superceded by sound intensity mapping.

In 1985 Brüel & Kjær introduced a new measurement technique entitled Spatial Transformation of Sound Fields (STSF) which enables a complete description of the sound field of a source to be obtained within a given solid angle. In the automotive industry in particular, STSF has been implemented in testing a wide variety of sources such as:

- Engines in test cells
- Whole vehicles (stationary and on dynamometers)
- Tyres mounted on vehicles on dynamometers
- Gear boxes on test stands
- Trailer refrigeration units
- Vehicles in wind tunnels

One reason why STSF has captured the imagination of automotive engineers is that it can be used to speed up many test procedures and thus cut costs in an increasingly competitive market, while simultaneously providing a new and more detailed understanding of the noise source. For example, in the research and development phase of a vehicle or a component, considerable time and effort is invested at outdoor proving grounds. As such tests are subject to the vagaries of the weather, the engineers would ideally like to make measurements close to the test object indoors and then calculate quantities such as radiation patterns or sound pressure level at some reference distance.

Few test cells, however, are large enough to accommodate direct measurements at the usual reference distance of 7,5 m from the centre line of the vehicle. With STSF the engineer can measure in the near field and calculate the far-field. These results can then be correlated with proving-ground measurements. Thus, whatever the weather, the testing can continue.

Another important problem facing engineers involved in a noise reduction program is to locate the main noise sources and to predict the effect, for example, of damping part of the engine. STSF can tackle this problem by the simulation of source attenuation.

To summarize the benefits of the technique it can be said that STSF:

- Speeds up testing
- Moves testing indoors
- Reveals more information about the source
- Simulates noise attenuation.

STSF was developed and continues to be refined in co-operation with vehicle manufacturers to produce a complete system based on standard hardware and easy-to-use menu-driven software.

To demonstrate how STSF performs in practice, Brüel & Kjær were invited to FIAT IVECO (Industrial Vehicle Company) in Torino, Italy, where two such systems are installed to perform measurements on:

1. Engines in a test cell
2. Cargo vans mounted on a chassis dynamometer.

This Application Note presents some of the results obtained.

What is STSF?

Spatial Transformation of Sound Fields is a term introduced by Brüel & Kjær to denote a powerful, sound field measurement and calculation technique. It involves a scan using an array of transducers over a planar surface close to the source under investigation. From the cross spectra measured during the scan, a principal component representation of the sound field is extracted. Any power descriptor of the near field (intensity, sound pressure etc.) can be investigated by means of near-field acoustical holography (NAH) while the more distant field can be determined by application of Helmholtz' integral equation.

The theoretical foundation of the cross spectrum principal component technique implemented in STSF has been discussed by J. Hald in [1]. The advantage of the STSF technique compared to a number of acoustical holography techniques have been demonstrated in the same article [1]. The practical implementation and some applications are described in [2].

Practical STSF systems

The STSF systems installed at IVECO are similar to the one depicted in Fig. 1. Full specifications are given in [3]. The engine test group has a system based on the narrow-band FFT Dual Channel Analyzer Type 2032 whilst the whole vehicle group has a Dual Channel Real-time Frequency Analyzer Type 2133 capable of measuring cross spectra in $1/3^{rd}$ or $1/12^{th}$ octave bands. Both systems employ a microVAX II computer and a compatible software package.

Measurements in the engine test cell

Measurements were performed in a large semi-anechoic test cell on a 6 cylinder diesel engine under various conditions. An important goal was to test the reproducibility of the measurements. The main test parameters are given in Table 1.

After a short warm up period, the engine was run at constant load throughout the measurement (Table 1). The measurement grid was defined over the top surface of the engine at a distance corresponding closely to the spacing chosen for the grid. Thus for IV1 & IV2 the distance between the scan positions, i.e. the spacing in the grid, was 0,1 m and this was also the distance to the nearest part of the engine block. For IV3 the spacing in the grid was 0,07 m and the distance to the engine block from the scan plane was 0,1 m.

In all three measurements, the same five reference microphones were used, distributed close to the engine block. Two multiplexers were required by the scan microphones and the scanning itself was performed by a robot under the control of the STSF software. Fewer scan microphones could have been used, but then multiple scans would have had to be made: e.g. for measurement IV3, 10 microphones were used and scanned twice to cover the entire scan area.

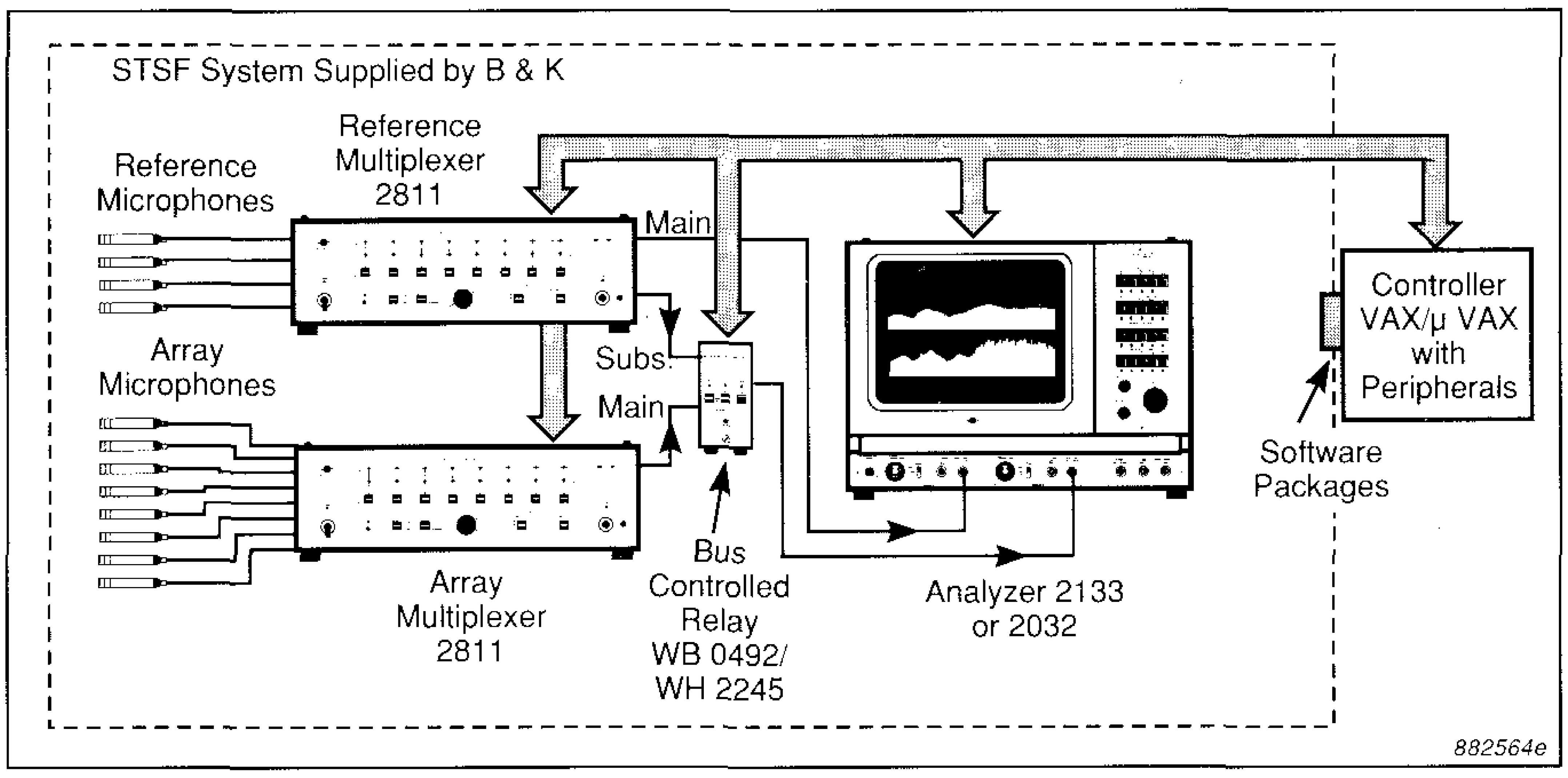

Fig. 1. STSF System Type 9606 uses Type 2032 while Type 9607 uses Type 2133

Test	Load	Measurement grid	Spacing in grid	Number of scan mics.	Total meas. time
IV1	Full load 380 hp 2000 rpm	13 × 16 208 points	0,1 m	13	1,5 h
IV2	Idling 512 rpm	13 × 16 208 points	0,1 m	13	1,5 h
IV3	Full load 380 hp 2000 rpm	20 × 22 440 points	0,07 m	10	3 h
IV4	120 hp 3400 rpm	10 × 33 330 points	0,25 m	10	3 h

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Table 1. Measurement parameters. Tests IV1, IV2 & IV3 were performed on the diesel engine. Test IV4 was made on a cargo van

Frequency range

The upper limiting frequency of an STSF measurement is determined by the spacing between the measurement points. At least 2 points per wavelength must be sampled otherwise spatial aliasing can occur. Obviously the higher the upper frequency desired, the finer the grid mesh must be and the longer time the measurement takes. There is thus a tangible trade-off between the amount of detail required from the measurement, the frequency range and the total time available.

The lower limiting frequency is defined to a large extent by the size of the scan area which should be at least one wavelength (preferably two) in width at the lowest frequency of interest. More details are given in [1] and [2]. The upper and lower limiting frequencies for the measurements are given in Table 2.

Test	Lower Limiting Freq.	Upper Limiting Freq.
IV1	260 Hz	1700 Hz
IV2	260 Hz	1700 Hz
IV3	245 Hz	2450 Hz
IV4	70 Hz	686 Hz

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Table 2. Lower and upper limiting frequencies of the measurements

Measurement Procedure

A simplified flow diagram of an STSF measurement is shown in Fig. 2. For good results well-defined measurement conditions are required. Information on the number of references used, the grid size, environmental conditions, presence of a reflecting plane, etc. are entered into a measurements set-up and stored with the measured data (Fig. 3). Details are given in [2].

Before performing any calculation, the data are inspected and validated using the functions available in the software to compare the directly measured data with the results derived from the description of the sound field established by the STSF program. Good agreement is needed here in order to obtain accurate predicted values.

If necessary, data can be re-measured and replaced. There will always

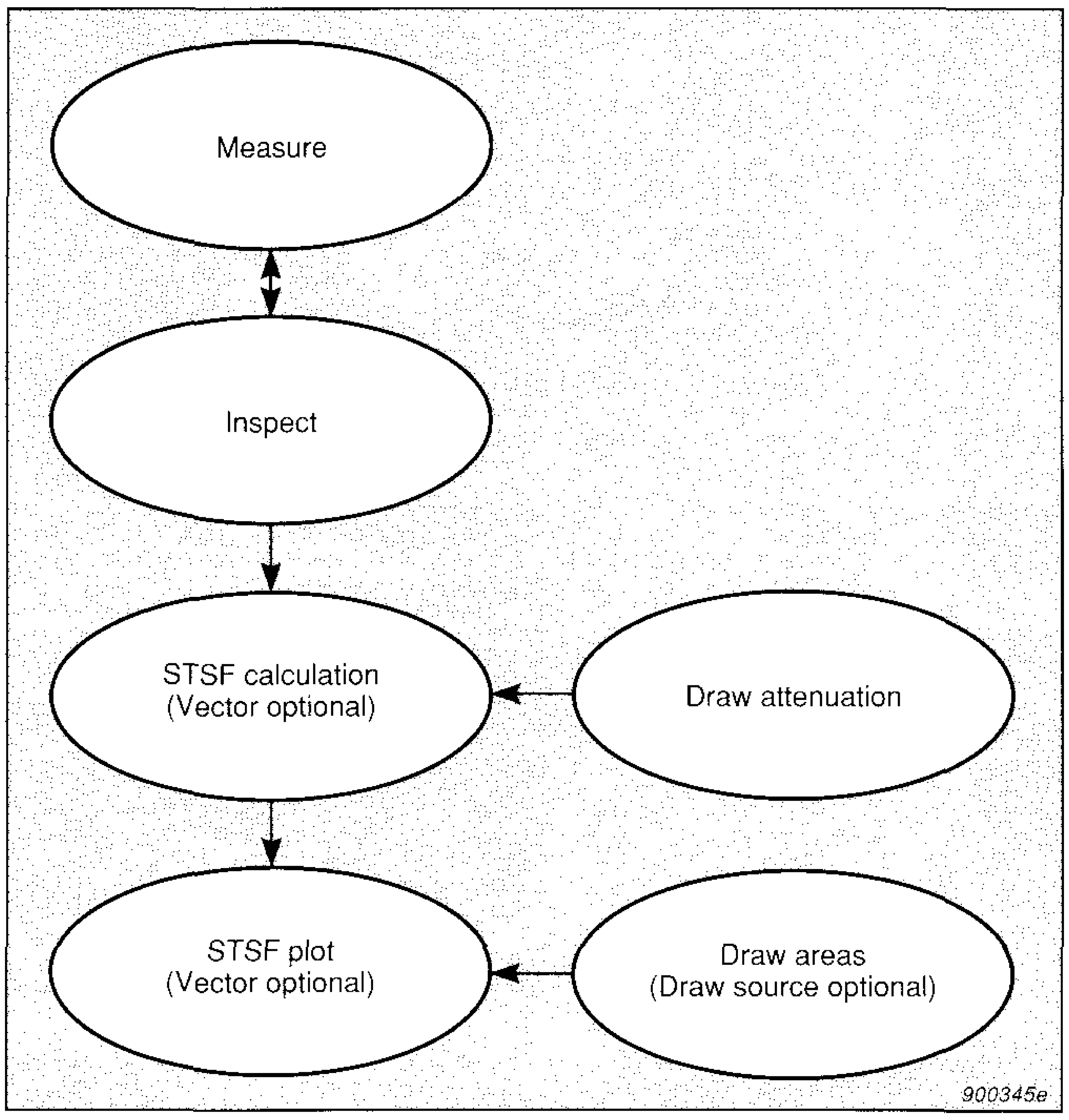
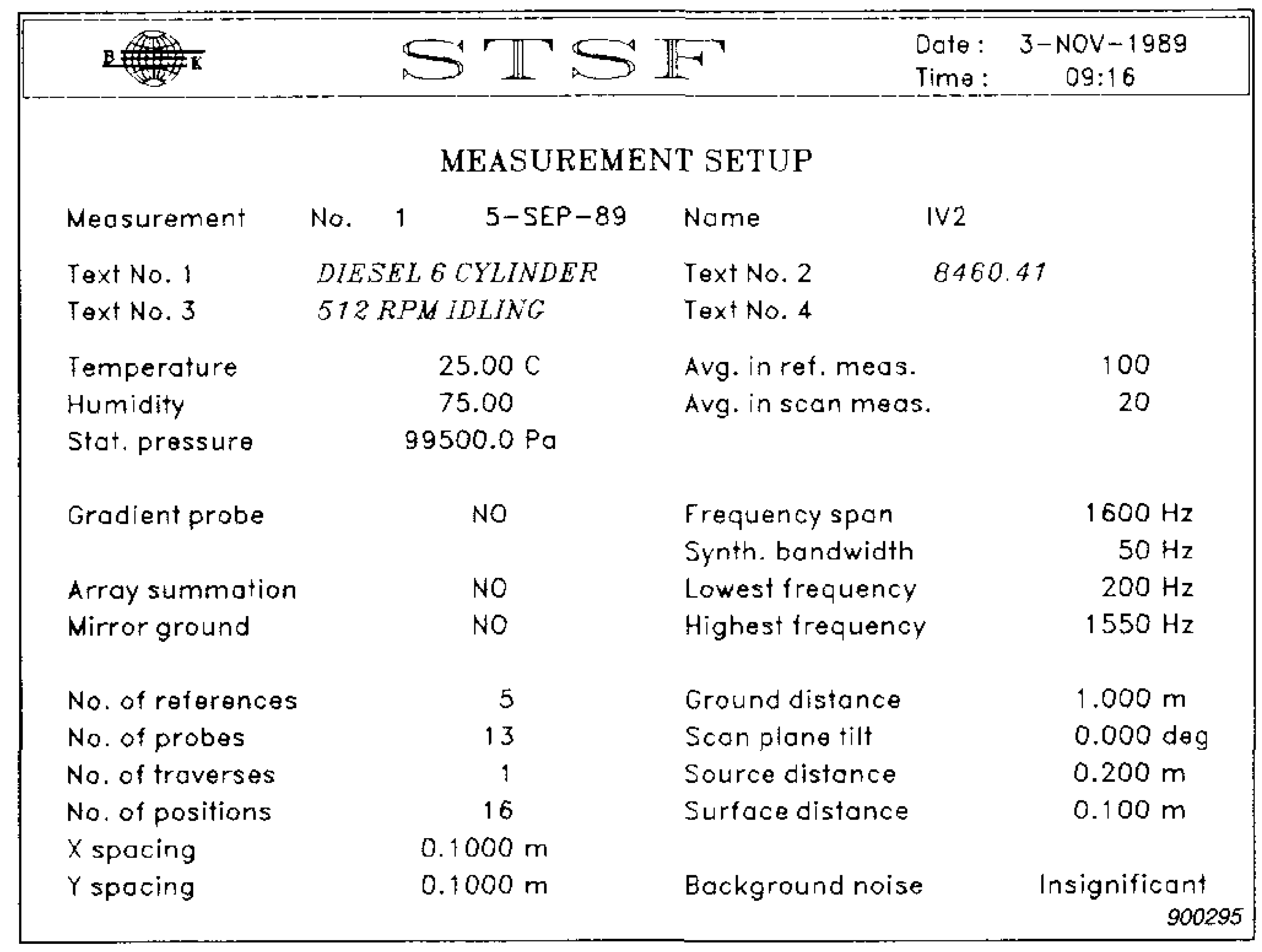


Fig. 2. Simplifed flow diagram of STSF measurement



Measurement	No. 1 5-SEP-89		Name	IV2
Text No. 1	*DIESEL 6 CYLINDER*		Text No. 2	*8460.41*
Text No. 3	*512 RPM IDLING*		Text No. 4	
Temperature	25.00 C		Avg. in ref. meas.	100
Humidity	75.00		Avg. in scan meas.	20
Stat. pressure	99500.0 Pa			
Gradient probe	NO		Frequency span	1600 Hz
			Synth. bandwidth	50 Hz
Array summation	NO		Lowest frequency	200 Hz
Mirror ground	NO		Highest frequency	1550 Hz
No. of references	5		Ground distance	1.000 m
No. of probes	13		Scan plane tilt	0.000 deg
No. of traverses	1		Source distance	0.200 m
No. of positions	16		Surface distance	0.100 m
X spacing	0.1000 m			
Y spacing	0.1000 m		Background noise	Insignificant

Fig. 3. Set-up for measurements on diesel engine (IV2)

be some discrepancy between the directly measured and the calculated spectra at the scan microphones due to, e.g., non-stationarity of the source during the measurement, too short an averaging time at low frequencies, the use of an insufficient set of references, or uncorrelated background noise.

Results

All the engine measurements were performed using a narrow band Dual Channel FFT Analyzer Type 2032. The data stored, however, is in the form of synthesized constant bandwidth bands. The advantages of this synthesis is that the effects due to non-stationarity of the source are reduced, shorter averaging times are needed to obtain the necessary confidence level, and that there are far fewer values to be stored and manipulated (30 bands instead of 800). The results of IV1 & IV2 are presented in 50 Hz bandwidths whilst those for IV3 are in 100 Hz bandwidths.

Validation

Figs. 4 and 5 compare the directly measured sound pressure levels (open columns) to the calculated levels (black columns) for positions near the centre of the scan area for measurements IV1 and IV2 respectively. There is good agreement between the measured and calculated values up to the upper limiting frequency of the measurements.

Results for measurement IV3 were similar to IV1. Other features of the inspection procedure include a stationary check and virtual coherence analysis.

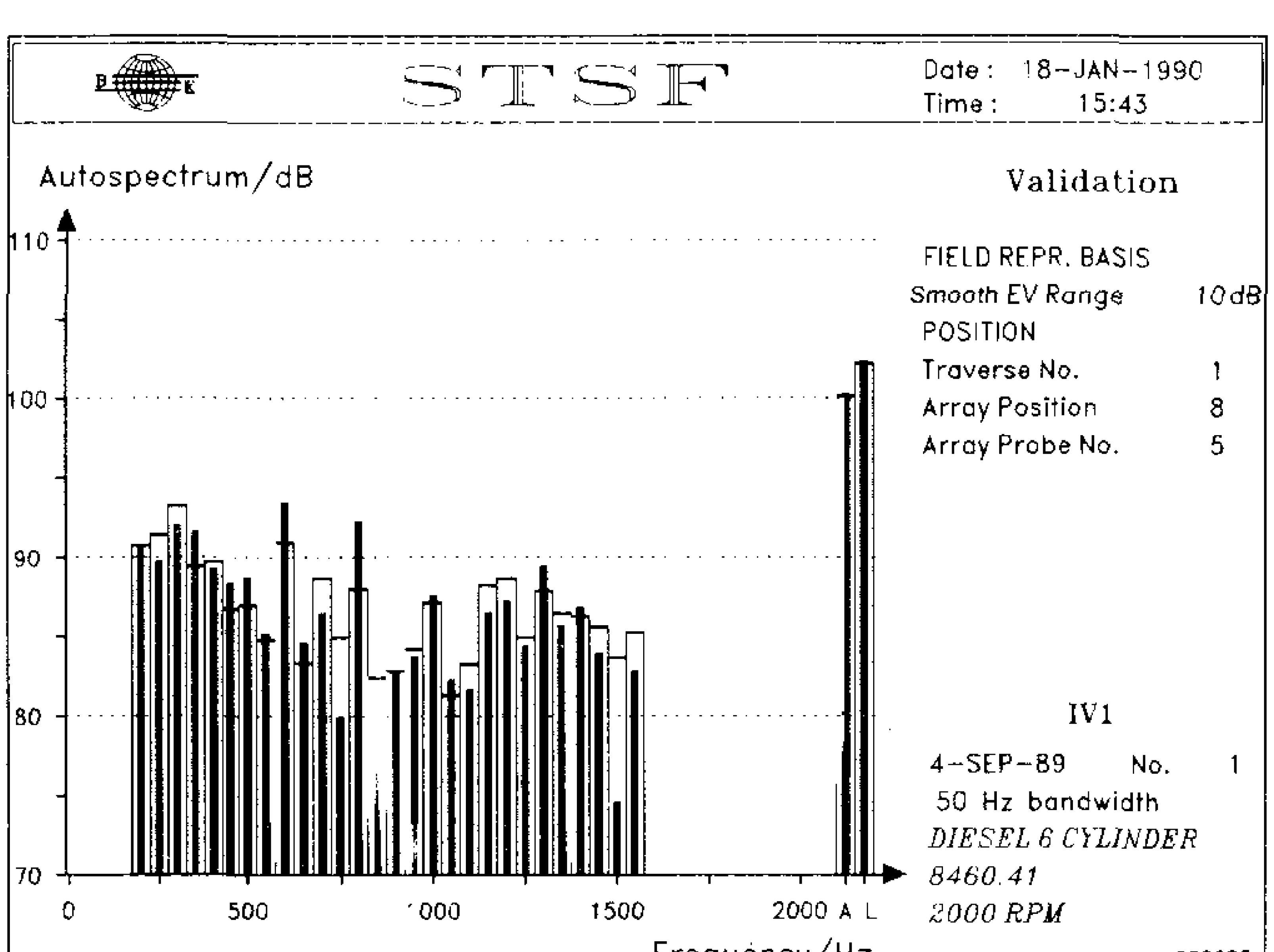


Fig. 4. Validation of data for measurement IV1

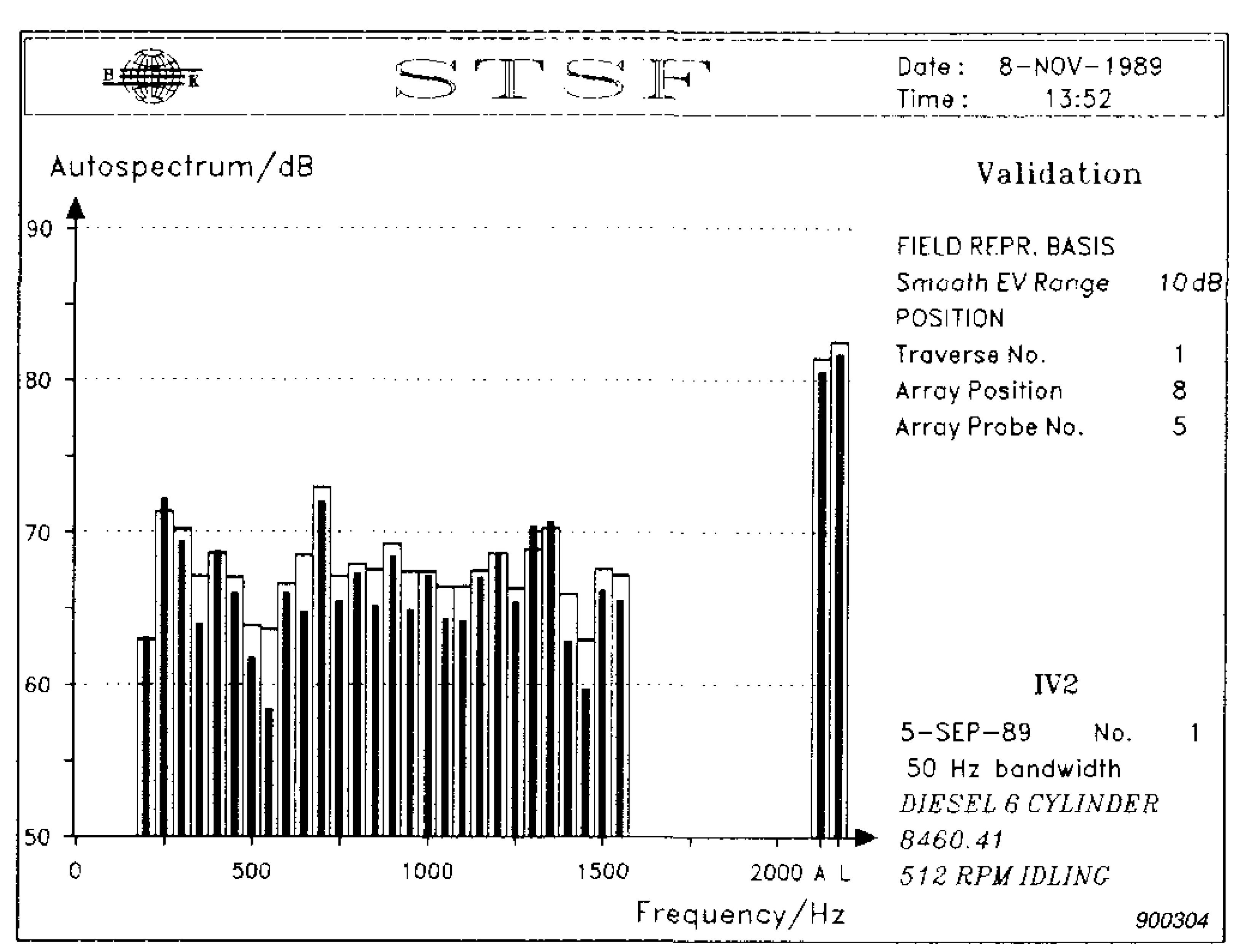


Fig. 5. Validation of data for measurement IV2

Contour plots and other representations of data

The most important frequency bands were seen to be 700 Hz and 1200 Hz. Contour plots of pressure, particle velocity, active intensity and reactive intensity were produced in the scan plane and close to the source using the NAH capability.

Examples of plots in the 50 Hz wide-band centred on 1200 Hz are shown in Figs. 6 to 9. The position of the cylinder heads is clearly seen. Four other ways of representing the data

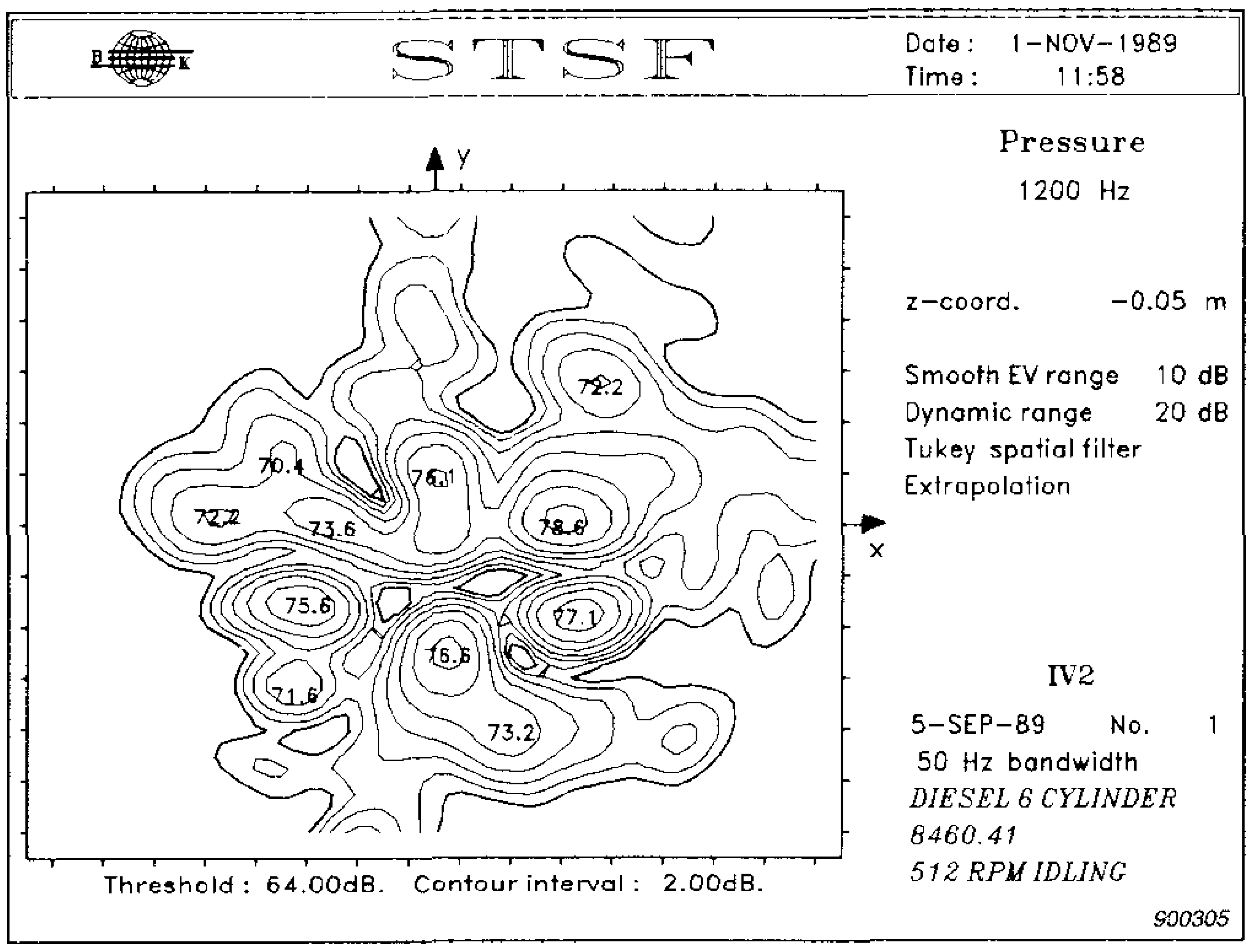


Fig. 6. Contour plots in the 50 Hz band centred on 1200 Hz at z = −0,05 m. Pressure

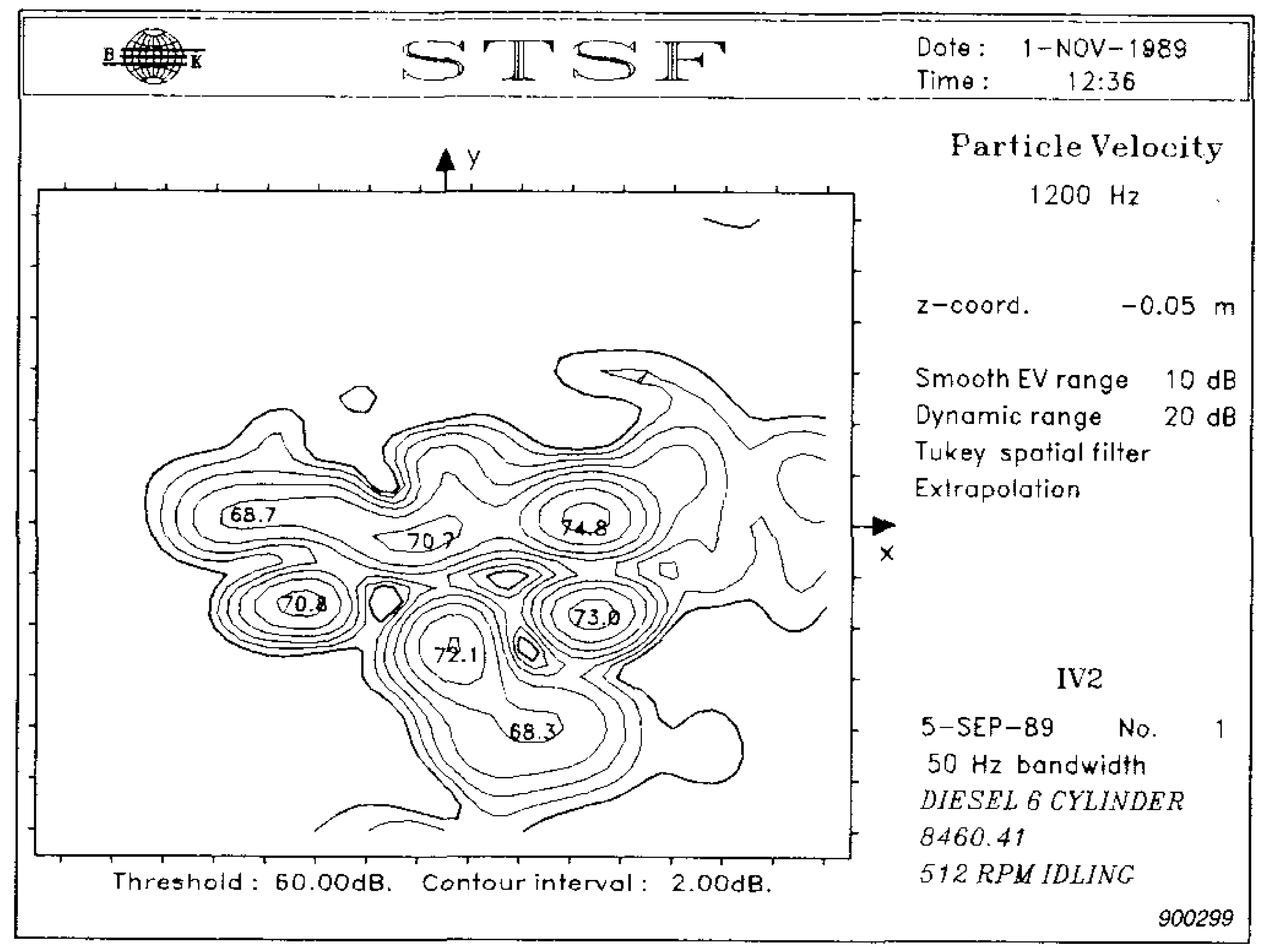


Fig. 7. Contour plots in the 50 Hz band centred on 1200 Hz at z = −0,05 m. Particle velocity

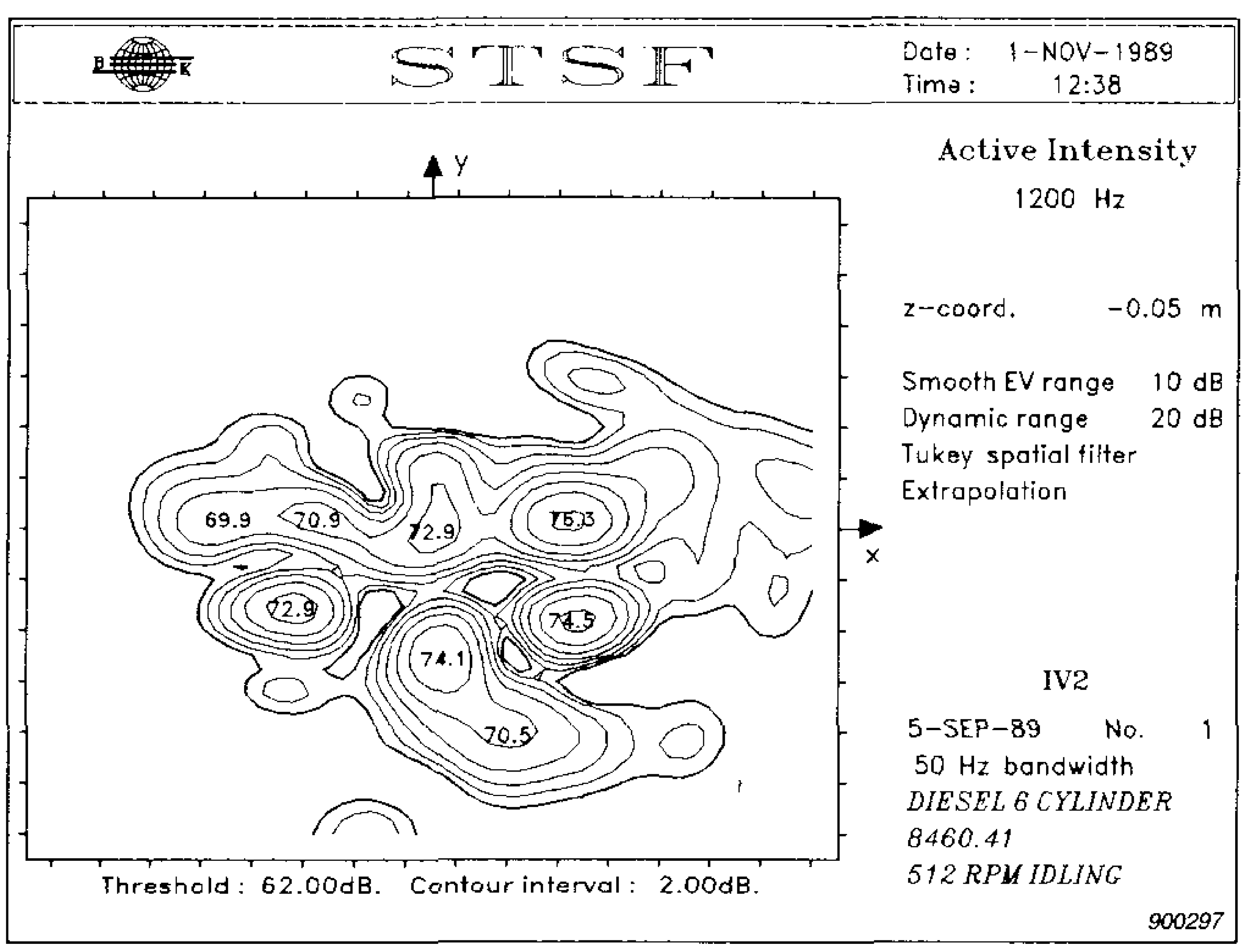


Fig. 8. Contour plots in the 50 Hz band centred on 1200 Hz at z = −0,05 m. Active intensity

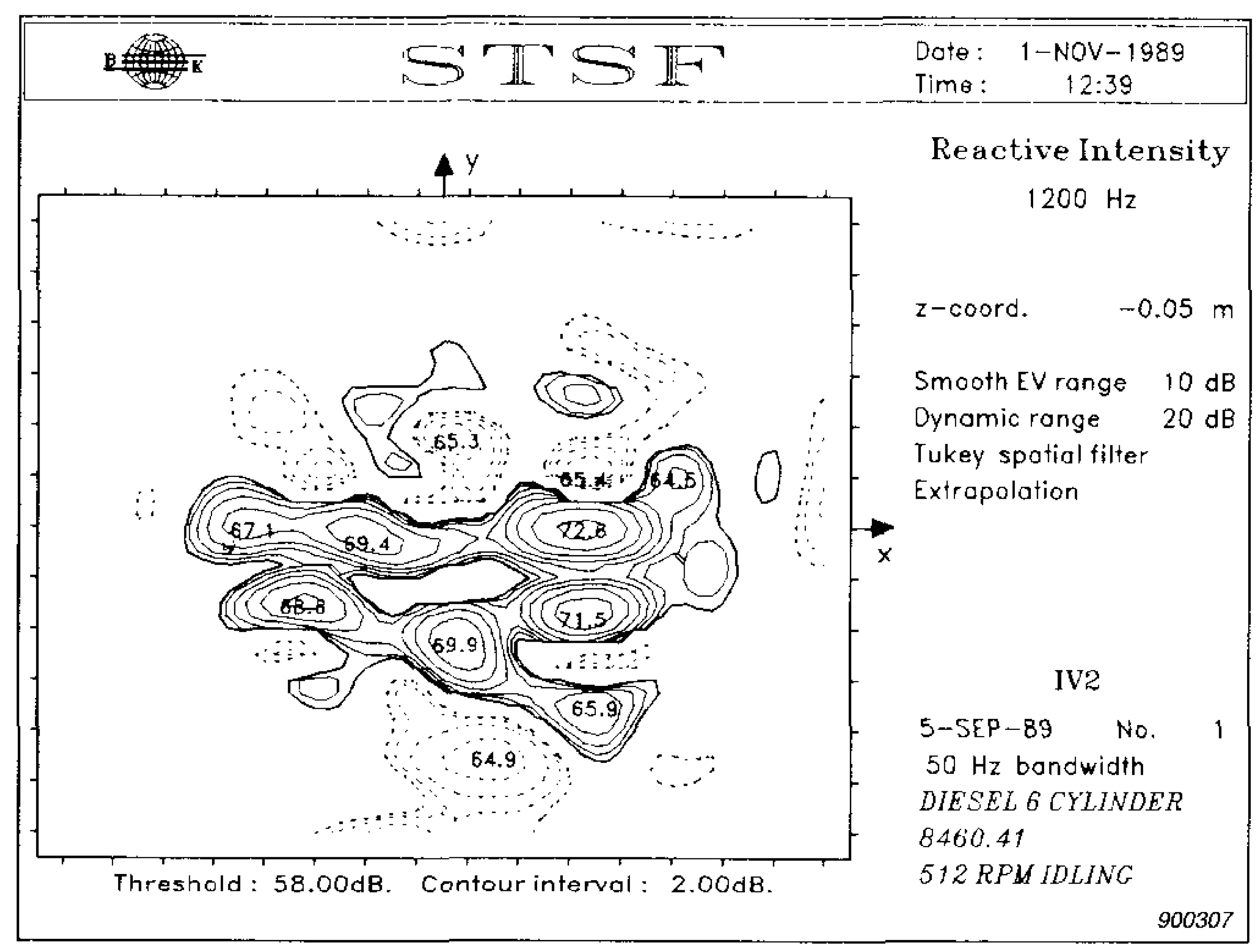


Fig. 9. Contour plots in the 50 Hz band centred on 1200 Hz at z = −0,05 m. Reactive intensity

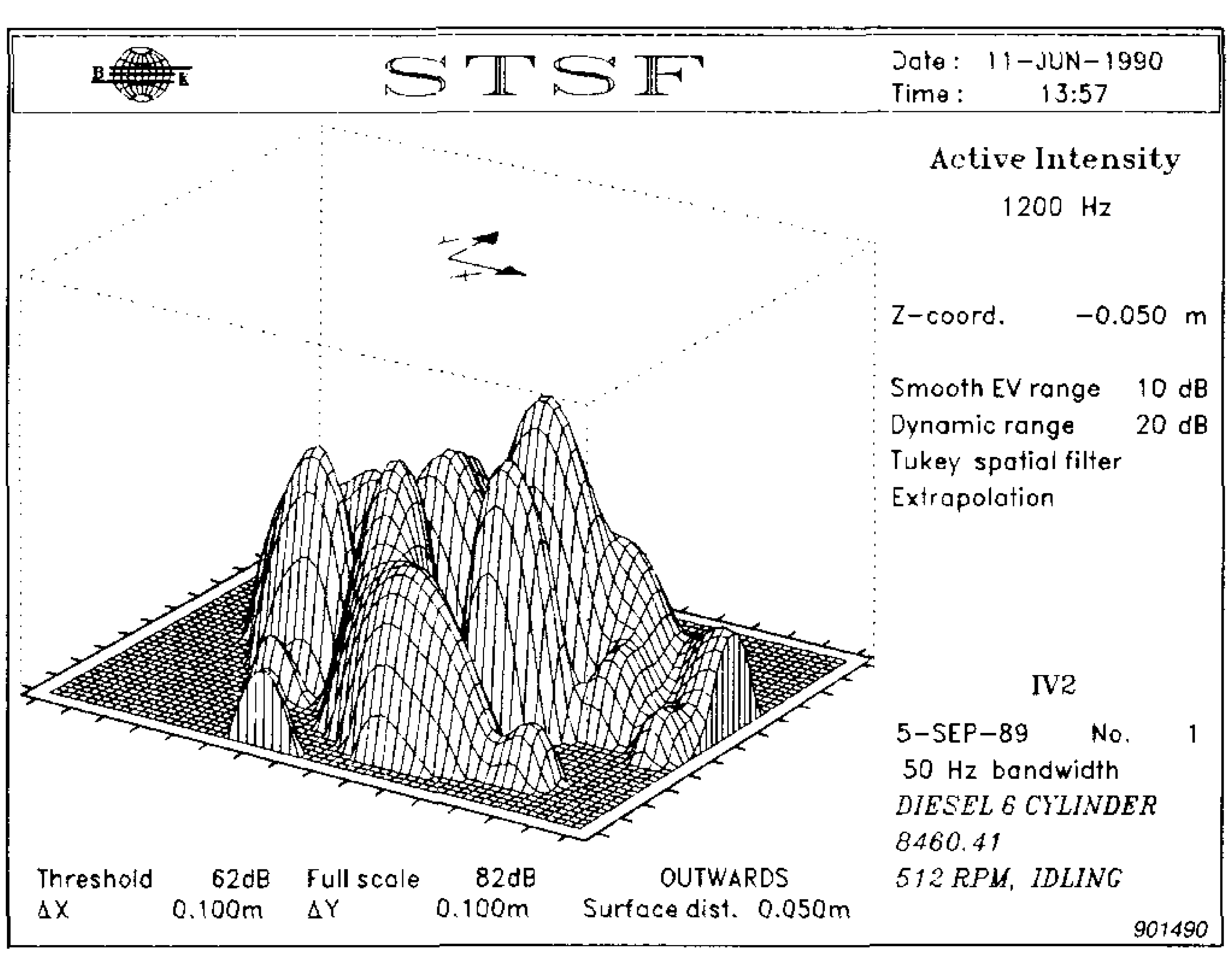


Fig. 10. Active intensity 3D plot

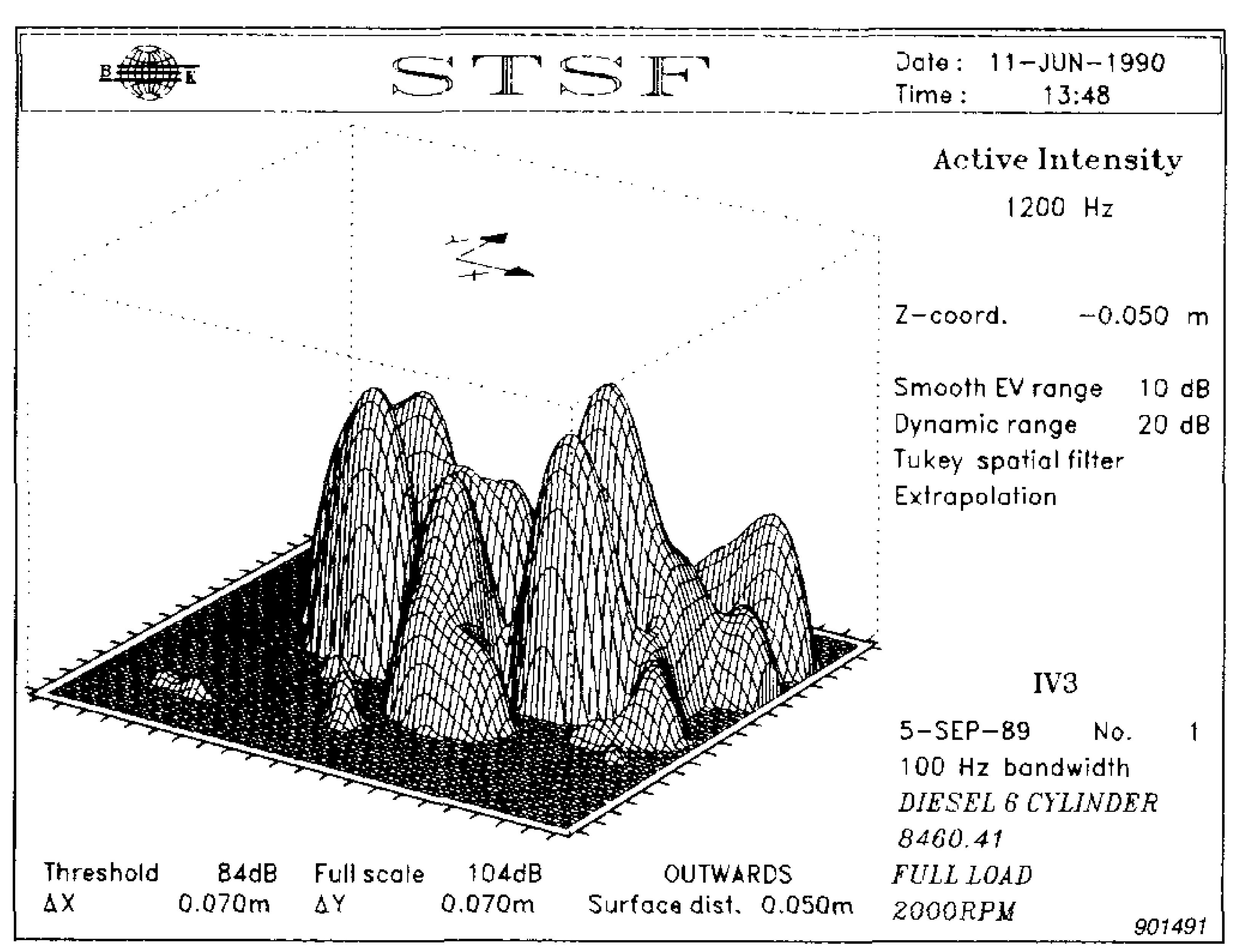


Fig. 11. Active intensity 3D plot at 2000 rpm

are shown in Figs. 10 to 15, two 3D plots, a radiation pattern, far-field sound pressure level and sound pressure level along a line respectively.

The focusing effect of the holography technique is illustrated in Figs. 16 & 17 which should be compared.

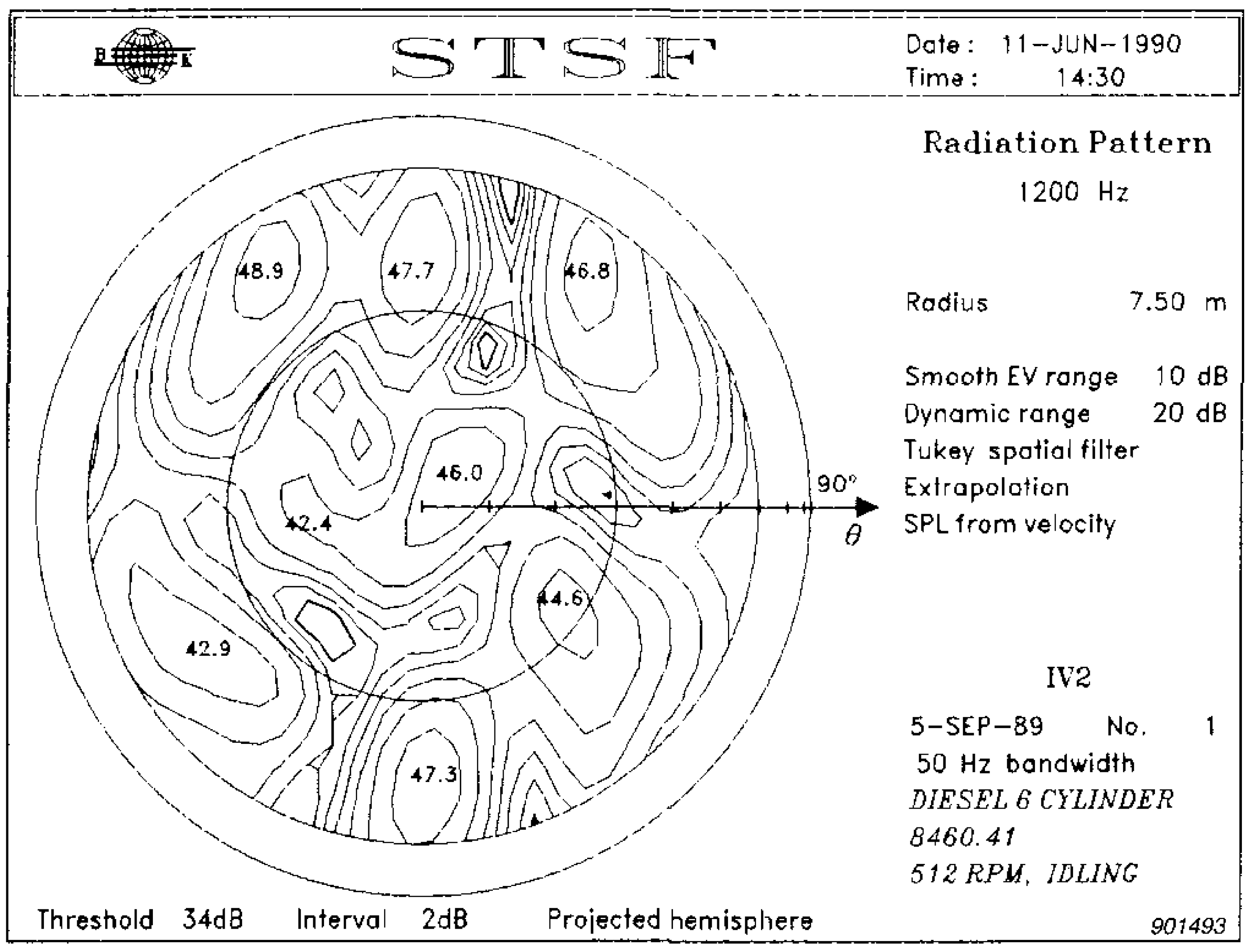


Fig. 12. Radiation pattern

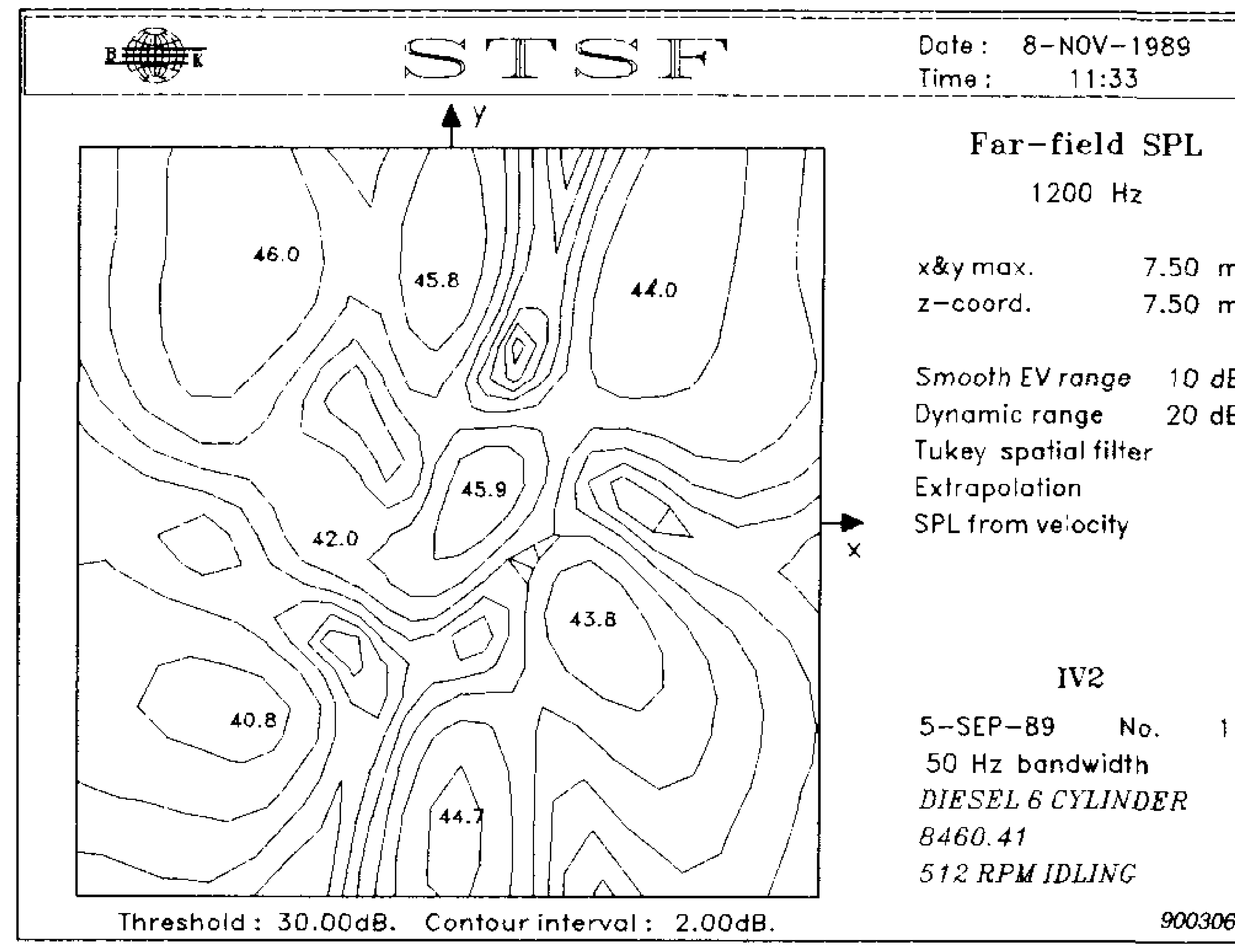


Fig. 13. Far-field sound pressure level

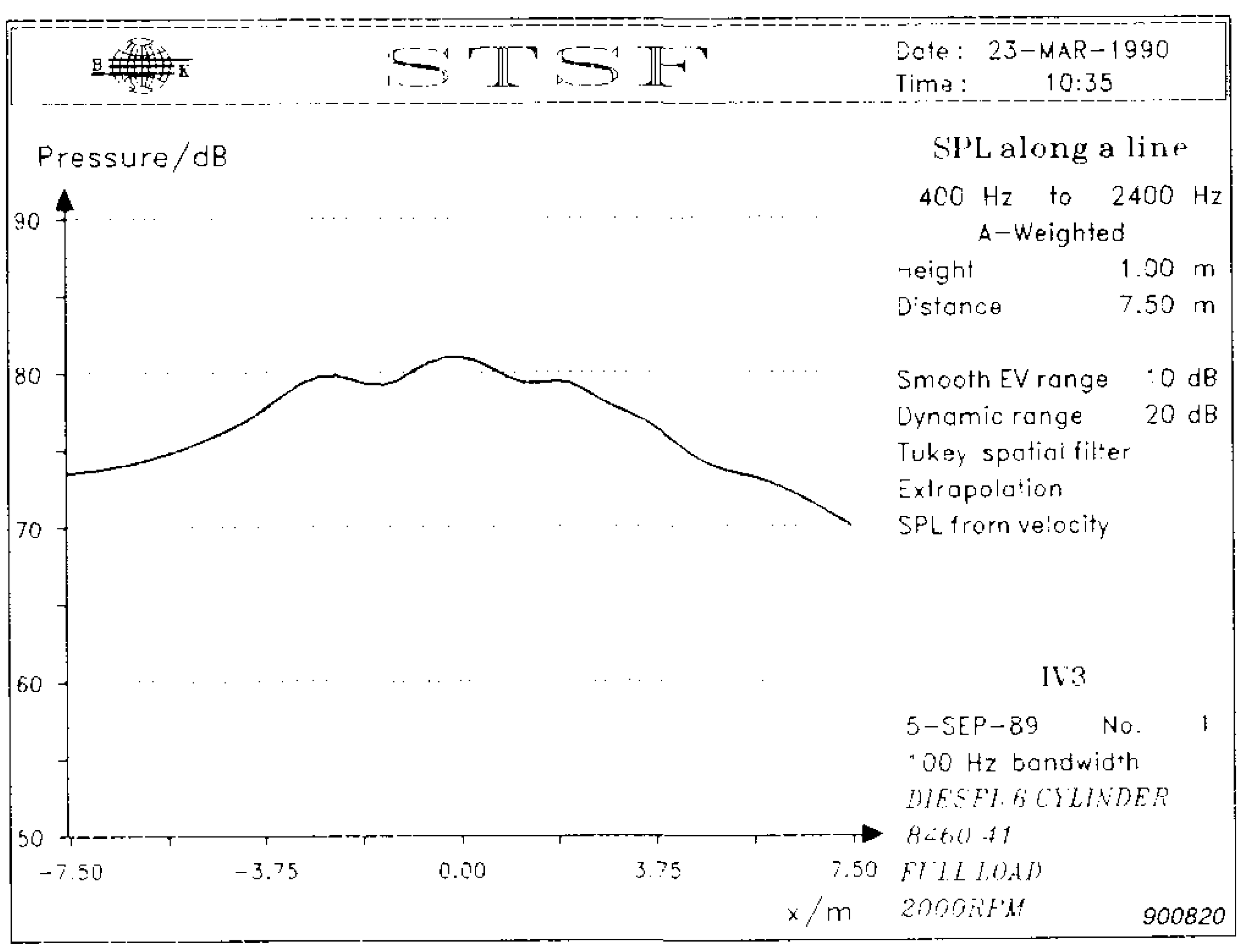


Fig. 14. A-weighted sound pressure level along a line in the frequency range 400 Hz to 2400 Hz. Full load

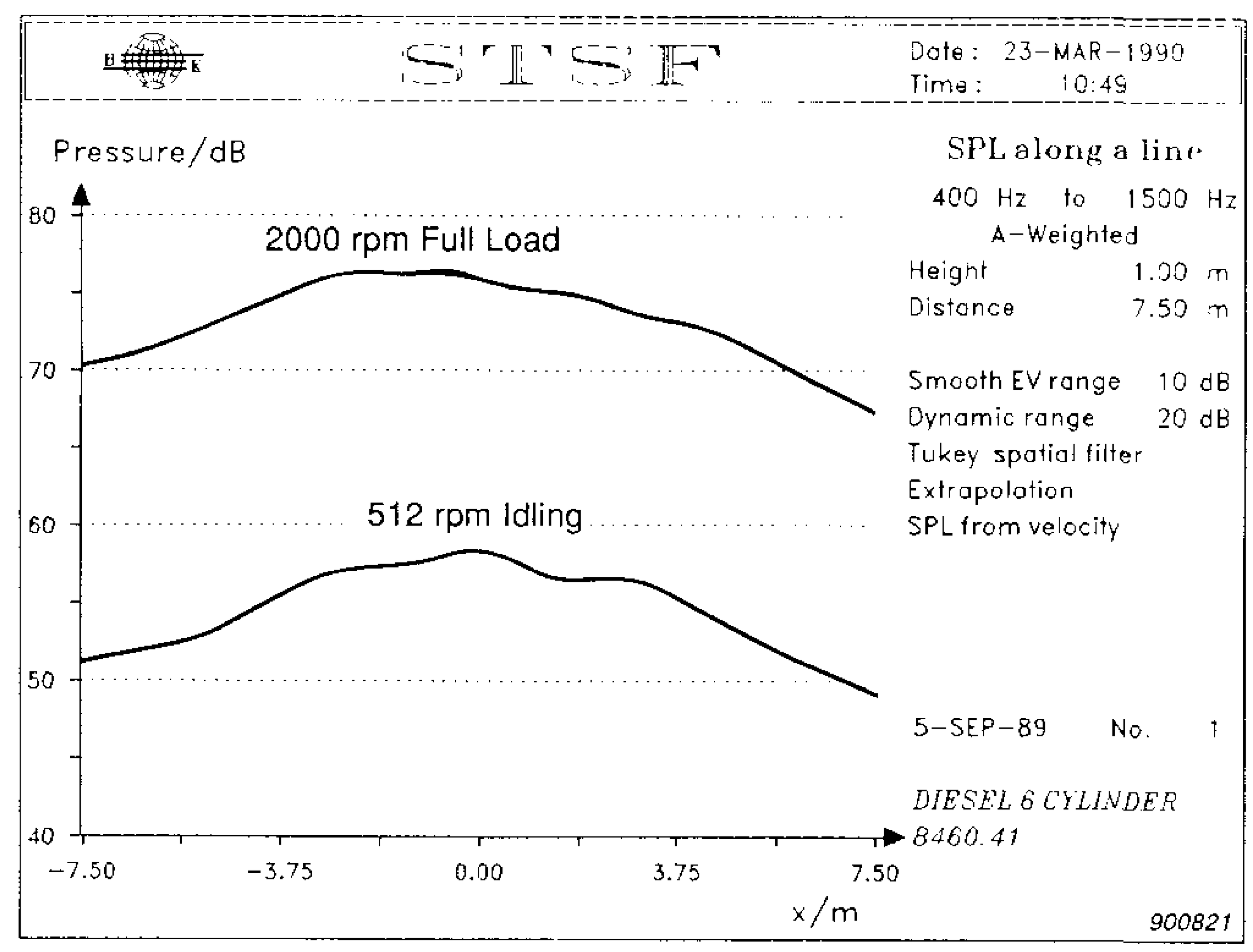


Fig. 15. Sound pressure level along a line for A-weighted spectrum between 400 Hz and 1500 Hz for the idling and the full load condition

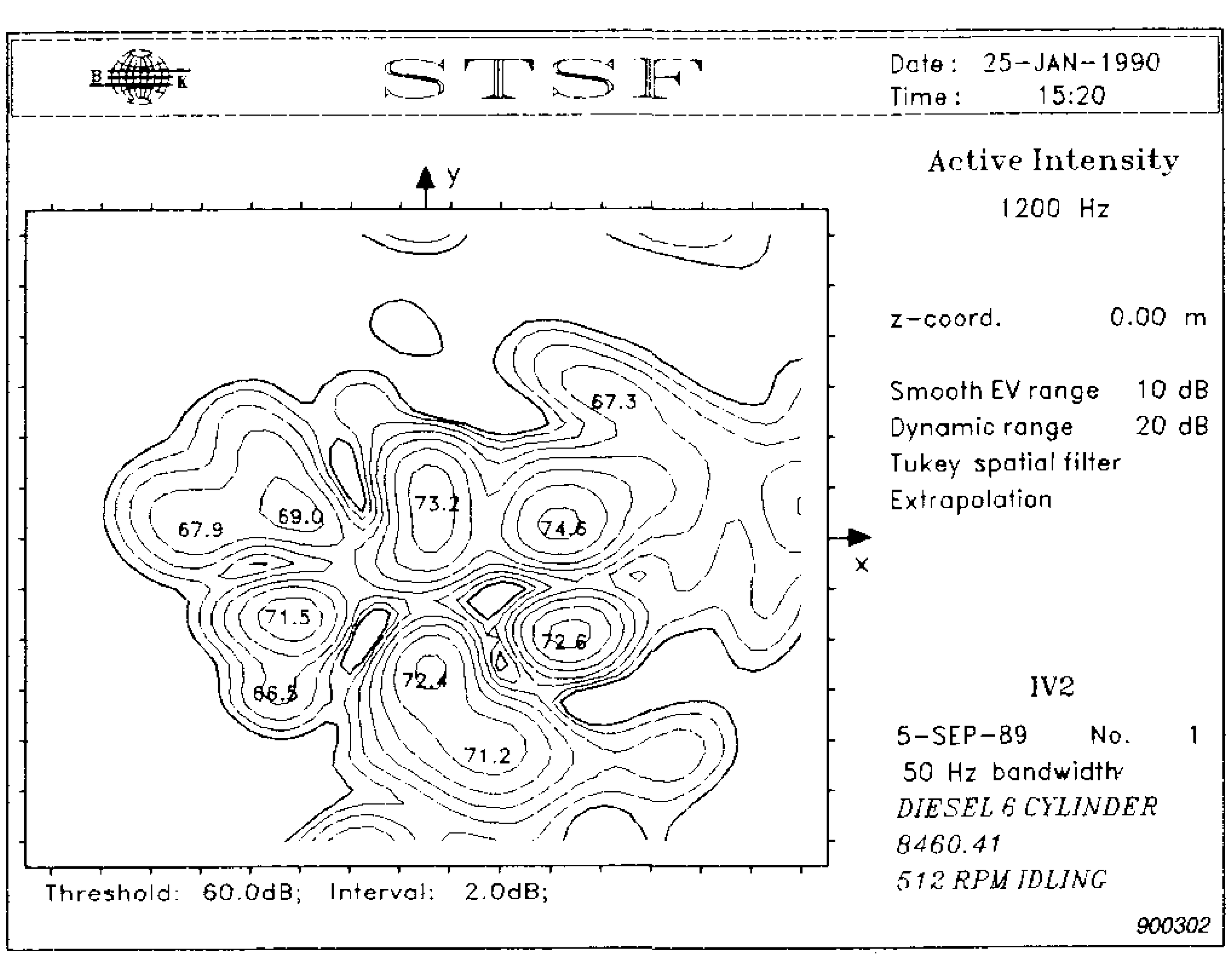


Fig. 16. Active intensity in the 50 Hz band centred on 1200 Hz at z = 0,0 m

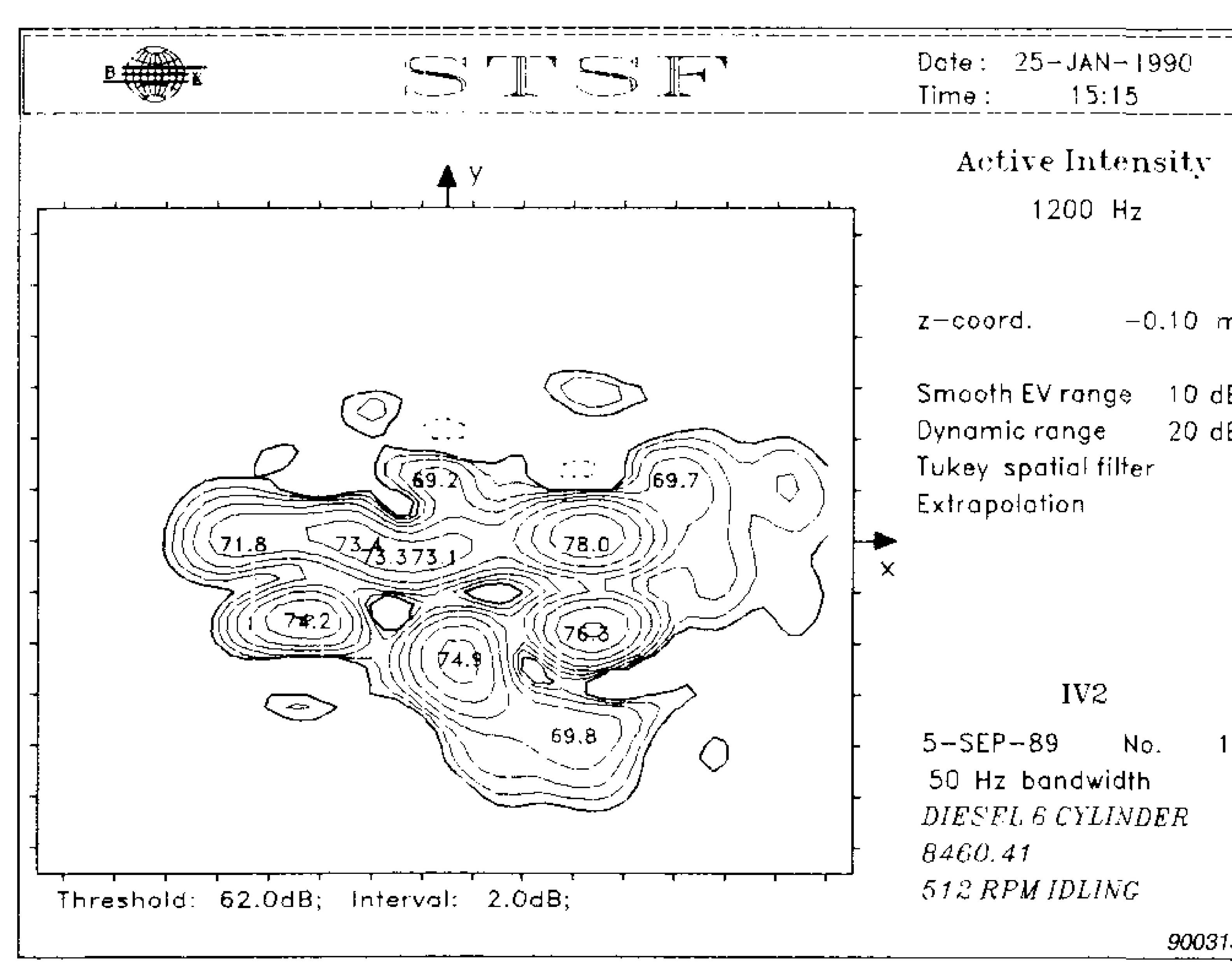


Fig. 17. Active intensity in the 50 Hz band centred on 1200 Hz at z = –0,1 m

Sound Power

The sound power through the measurement area, of the whole or part of the engine was obtained as a spectrum (Fig. 18) and as a graphical representation (Fig. 19). The graphics facility of the software was used to sketch the perimeter of the engine and the positions of the cylinders. In this way the relative contributions of the cylinders to the total sound power can be illustrated and calculated.

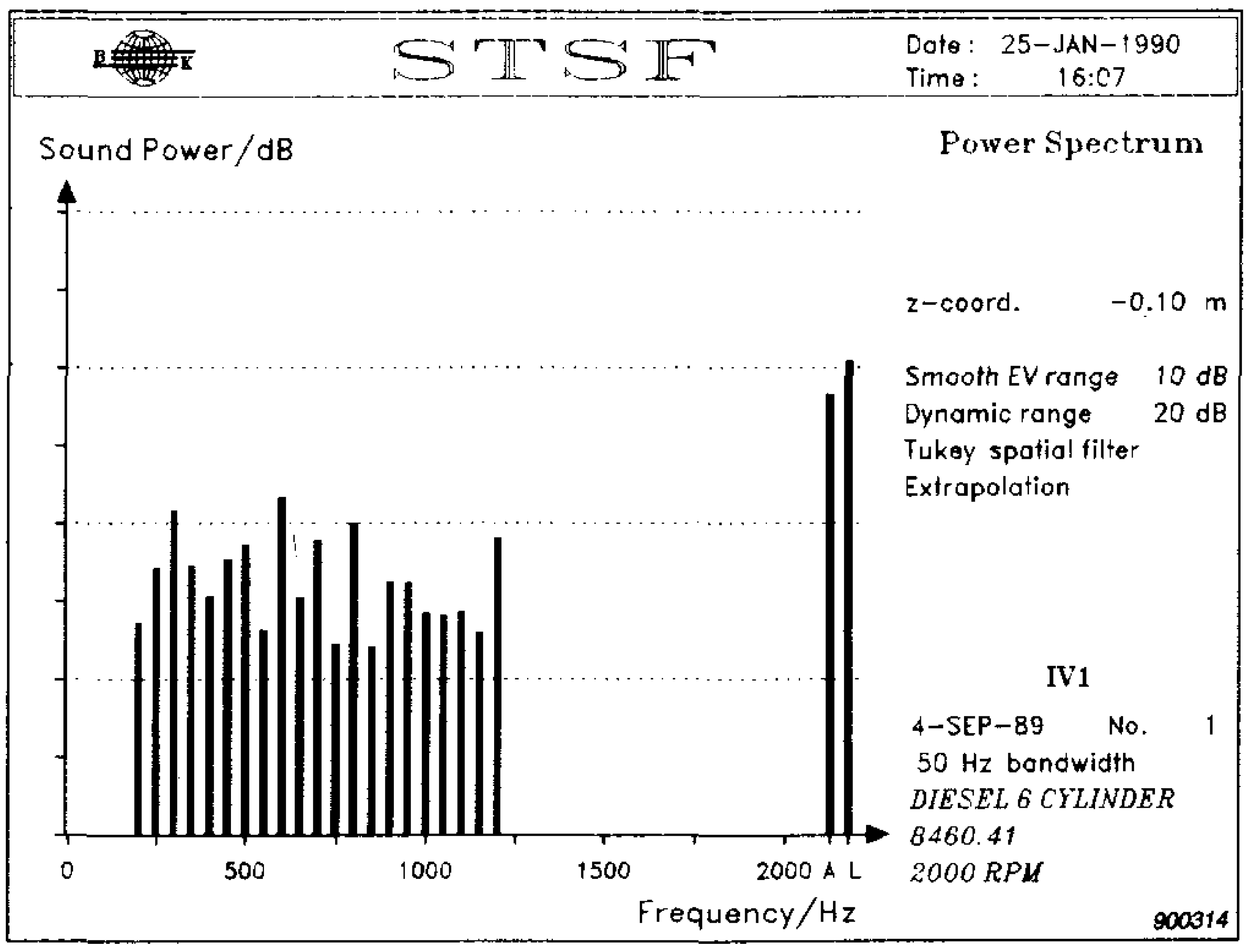


Fig. 18. Sound power spectrum of engine. 10dB per division on Y-axis

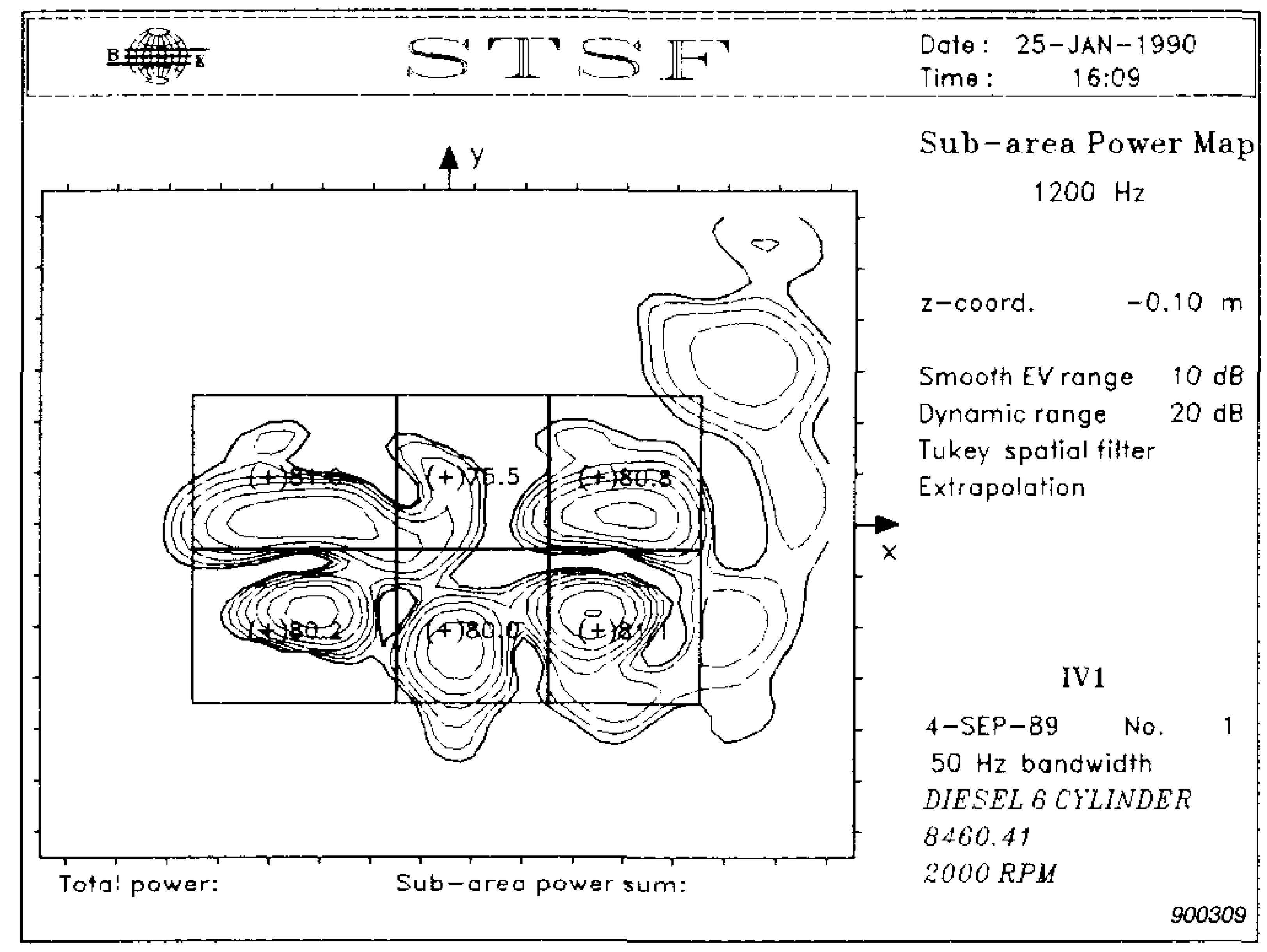


Fig. 19. Sub-area power map at z = –0,1 m no attenuation applied

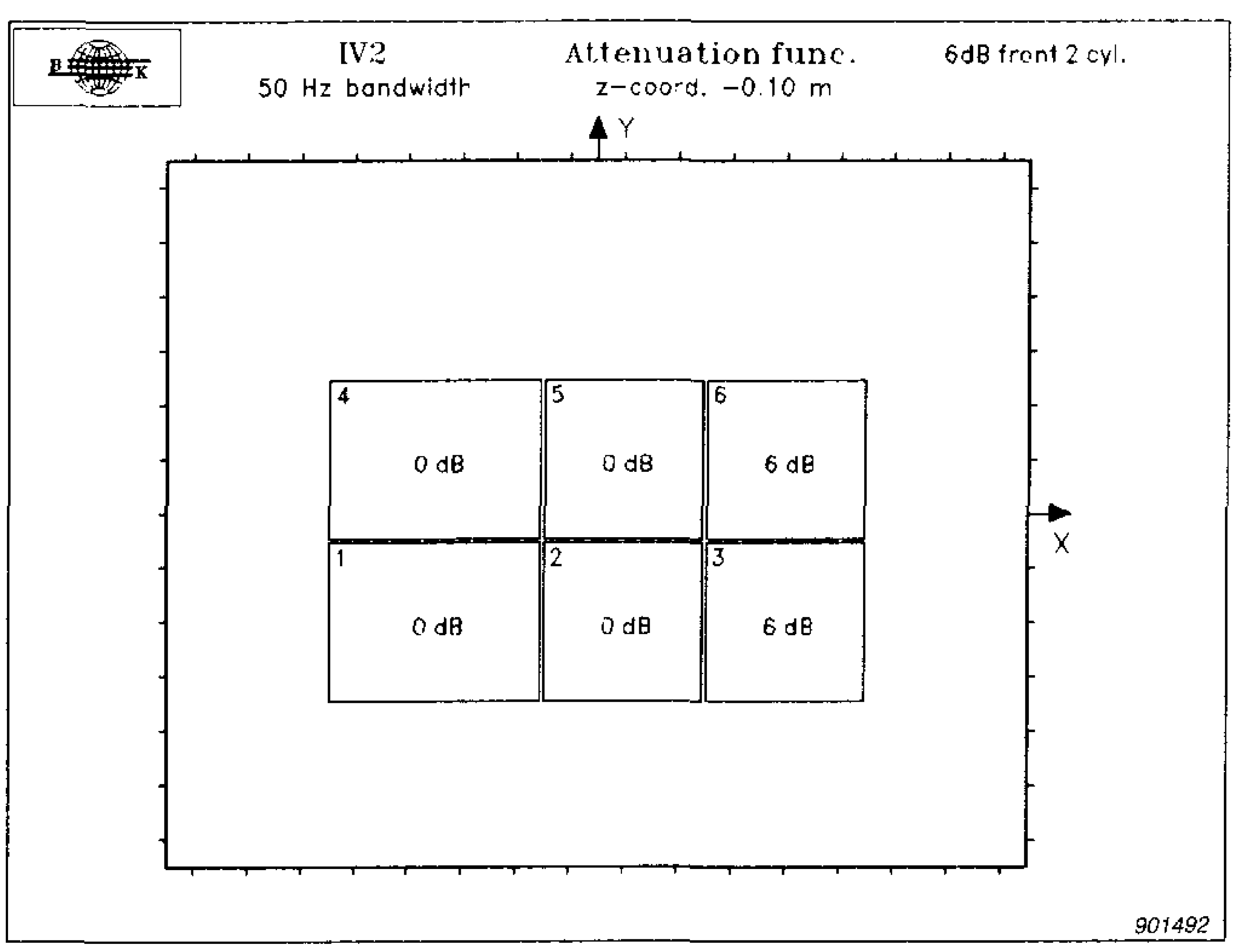


Fig. 20. Attenuation function imposed on the two front cylinders. The number in the upper left-hand corner identifies the area. The attenuation is given by the number in the lower right-hand corner

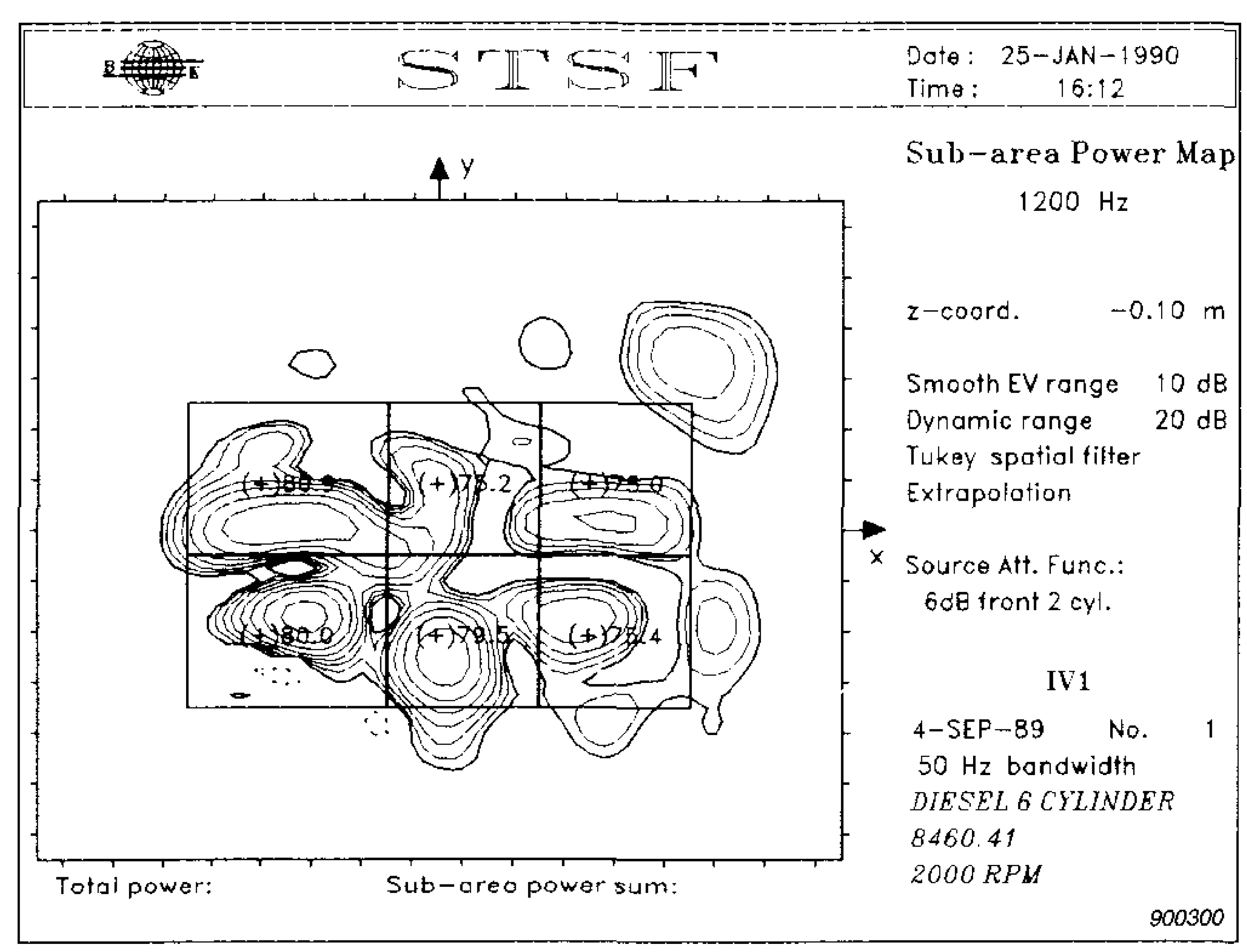


Fig. 21. Sub-area power map for IV1 at z = –0,1 m with attenuation applied

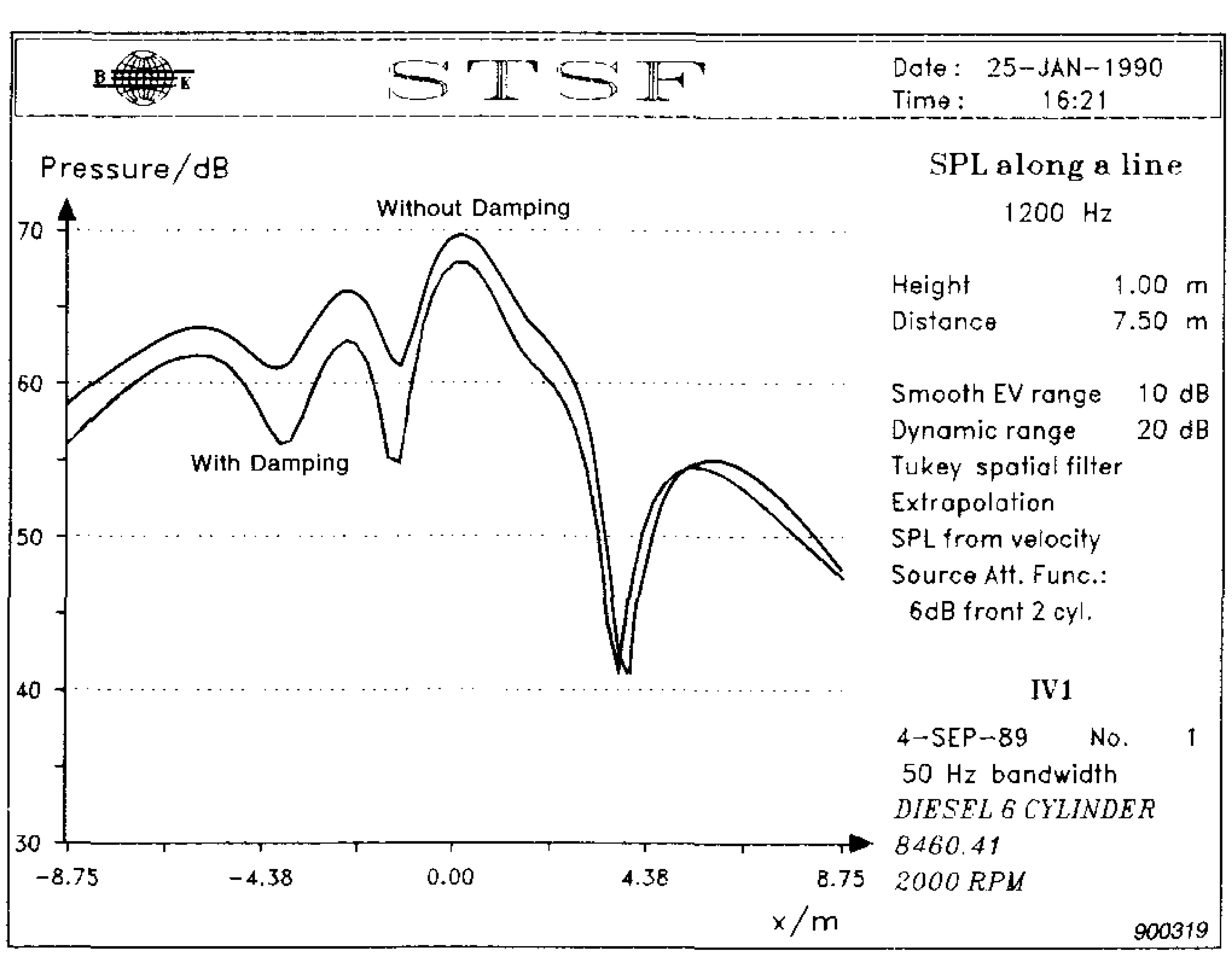


Fig. 22. Sound pressure level along a line at 7,5 m from scan area

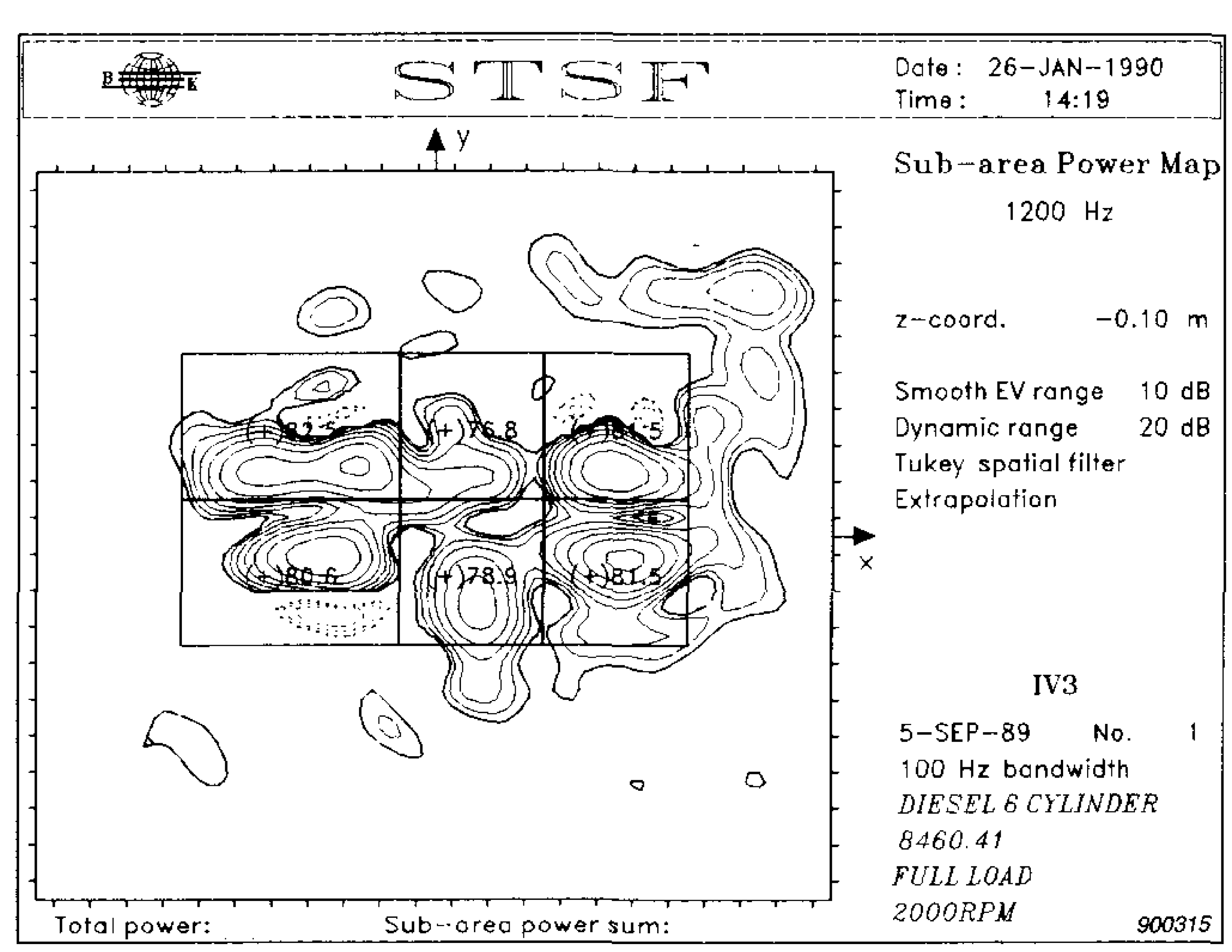


Fig. 23. Sub-area power map for IV3 at z = –0,1 m at 1200 Hz

Noise Reduction Simulation

By using the simulation of source attenuation facility, it was investigated how a reduction in the sound power due to the front two cylinders (Fig. 20) would affect the total sound power (Fig. 21), the radiation pattern and the sound pressure level along a line (Fig. 22).

Reproducibility

The reproducibility of the measurements was tested by comparing the sound power maps at various frequencies for measurements IV1 and IV3. The result for IV3 shown in Fig. 23 should be compared with Fig. 19, where it can be seen that measurements using different scan arrays, made on two consecutive days on an engine running under the same conditions, gave the sound powers listed in Table 3. The consistent results show that the operation of the engine could be controlled extremely accurately.

Measurement	Total power	Sub-area power
IV1	0 dB	–1,2 dB
IV3	+ 0,4 dB	–0,6 dB

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Table 3. Reproducibility of the measurements. The values are obtained from Figs. 19 & 23. The values are expressed relative to the total power of the IV1 measurement

Measurements on cargo van

Measurements were also performed on a cargo van mounted on a dynamometer using the same instrumentation. The main aim here was to test the suitability of the environment for STSF measurements. To prevent the vehicle from overheating, large cooling fans were used throughout the measurement. The measurement set-up is shown in Fig. 24.

The validation procedure indicates quite clearly that there was a significant amount of background noise and/or too few reference microphones were employed (Fig. 25). However, despite the poor measurement conditions a reasonable measurement was obtained.

The two frequency bands of interest are 250 Hz and 500 Hz. Active intensity contour plots at these frequencies are shown in Figs. 26 and 27. The main noise-radiating regions are seen to be the motor for 250 Hz and the exhaust system for 500 Hz.

Figs. 28 and 29 show the sound power calculated in the two bands of inter-

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MEASUREMENT SETUP

MEASUREMENT	No. 1 7-SEP-89	NAME	IV4
Text No. 1	IVECO lorry	Text No. 2	
Text No. 3	on dynomometer	Text No. 4	
Temperature	22.00 Celcius	Avg. in ref. meas.	80
Humidity	75.00	Avg. in scan meas.	20
Stat. pressure	100500.0 Pascal		
Gradient probe	NO	Frequency span	1600 Hz
		Synth. bandwidth	50 Hz
Array summation	NO	Lowest frequency	200 Hz
Mirror ground	YES	Highest frequency	1550 Hz
No. of references	6	Ground distance	1.250 m
No. of probes	5	Scan plane tilt	0.000 deg.
No. of traverses	2	Source distance	0.500 m
No. of positions	33	Surface distance	0.250 m
X spacing	0.2500 m		
Y spacing	0.2500 m	Background noise	Insignificant

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Fig. 24. Set-up for measurements on cargo van (IV4)

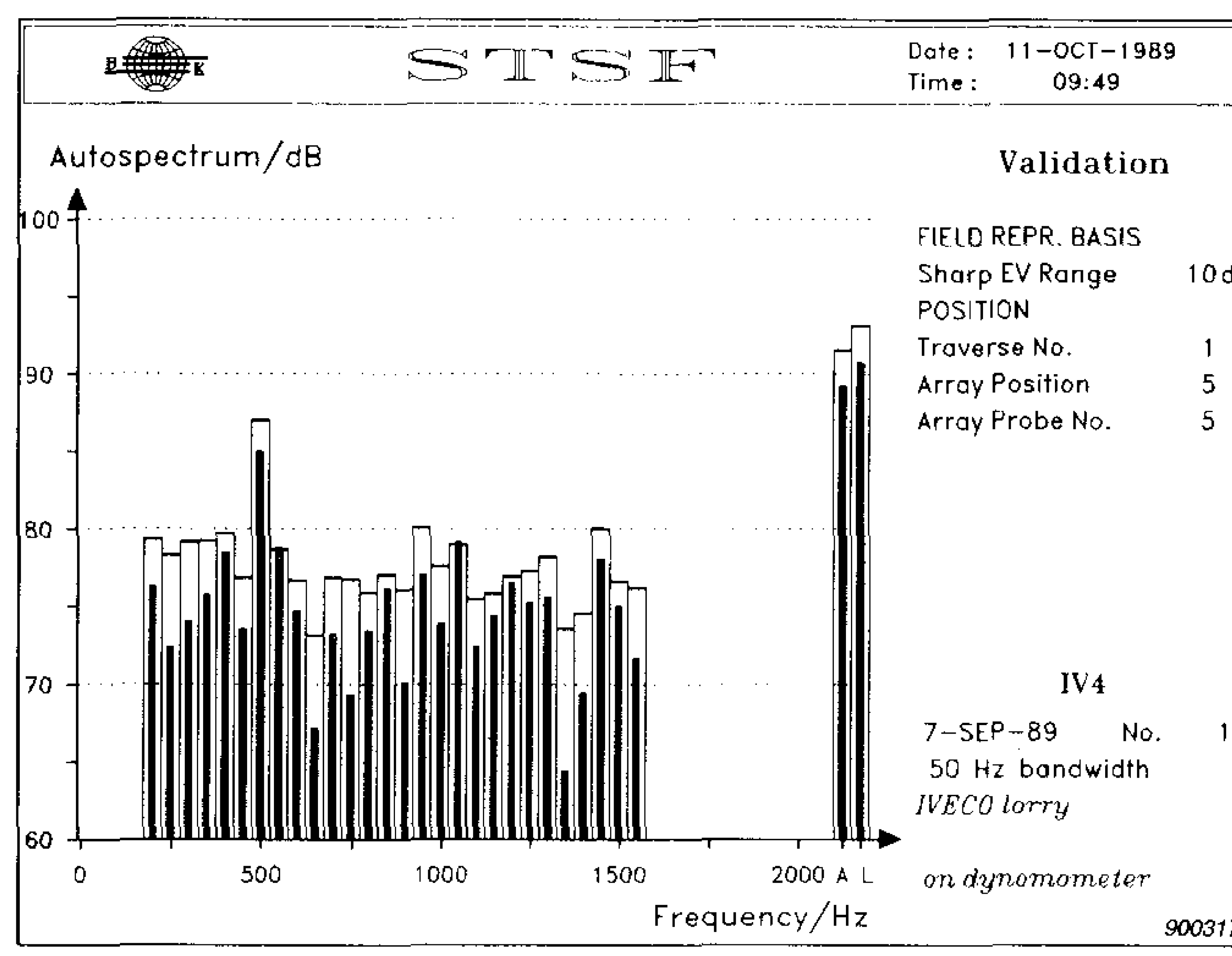

Fig. 25. Validation of data for IV4

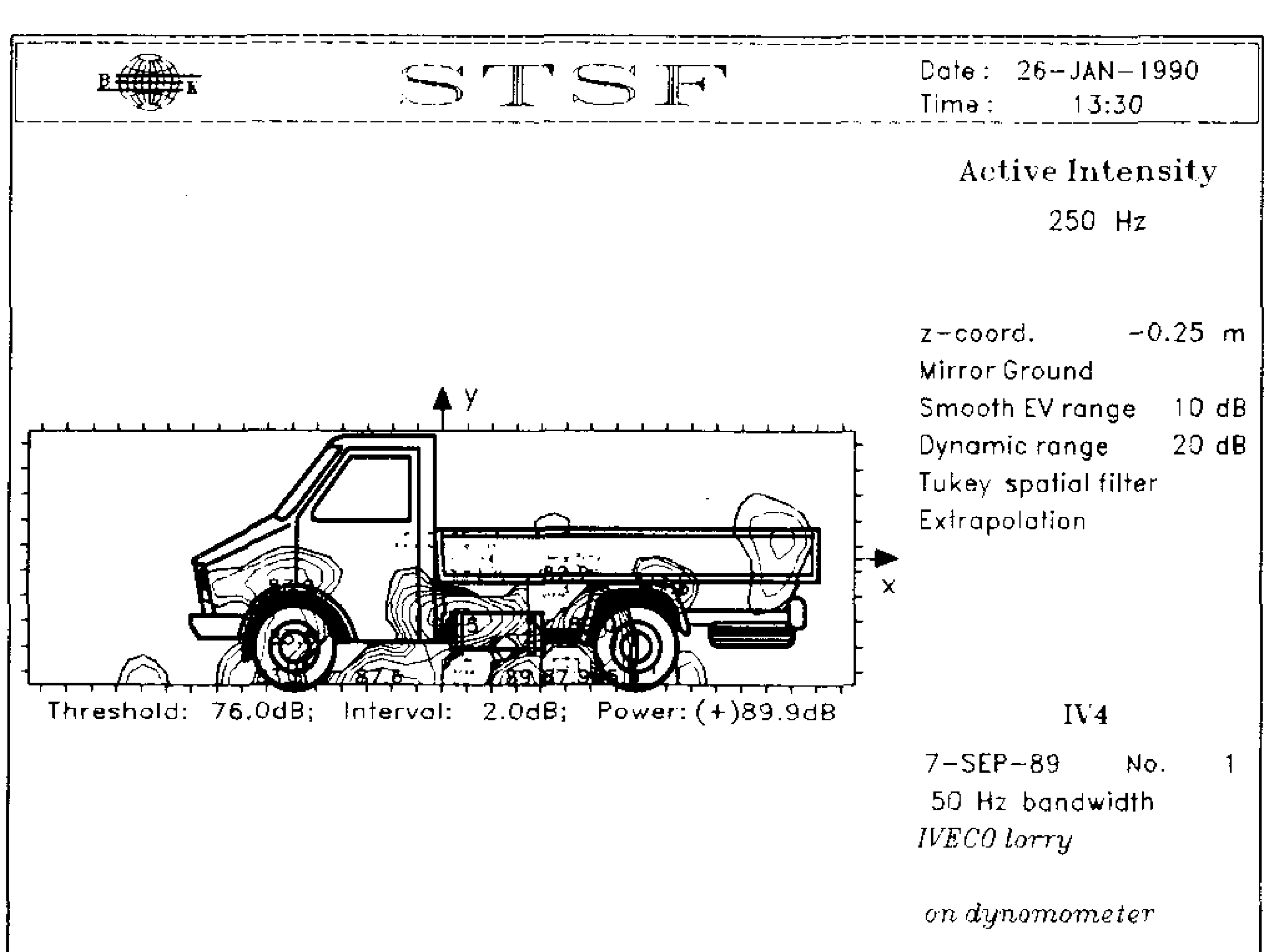

Fig. 26. Active intensity contour plot 250 Hz at z = –0,25 m

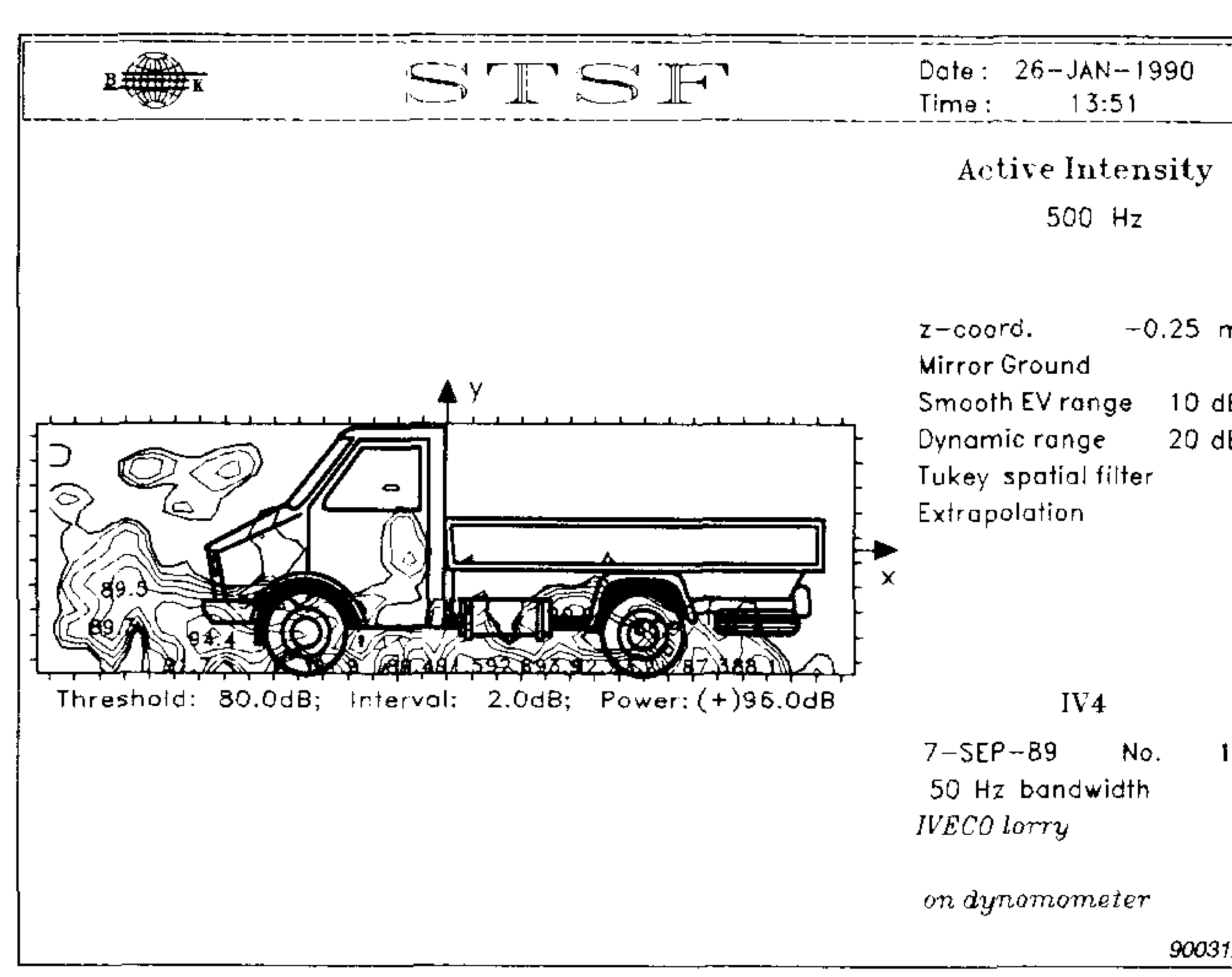

Fig. 27. Active intensity contour plot 500 Hz at z = –0,25 m

est while Figs. 30 and 31 shows the sound power after an attenuation of 6 dB has been applied to the motor and the exhaust. The sound pressure level along a line situated at 7,5 m from the centre line of the vehicle before and after attenuation is shown in Fig. 32.

The curves in Fig. 33 are similar to those in Fig. 32 except that the values are A-weighted in the frequency range 200 Hz to 700 Hz.

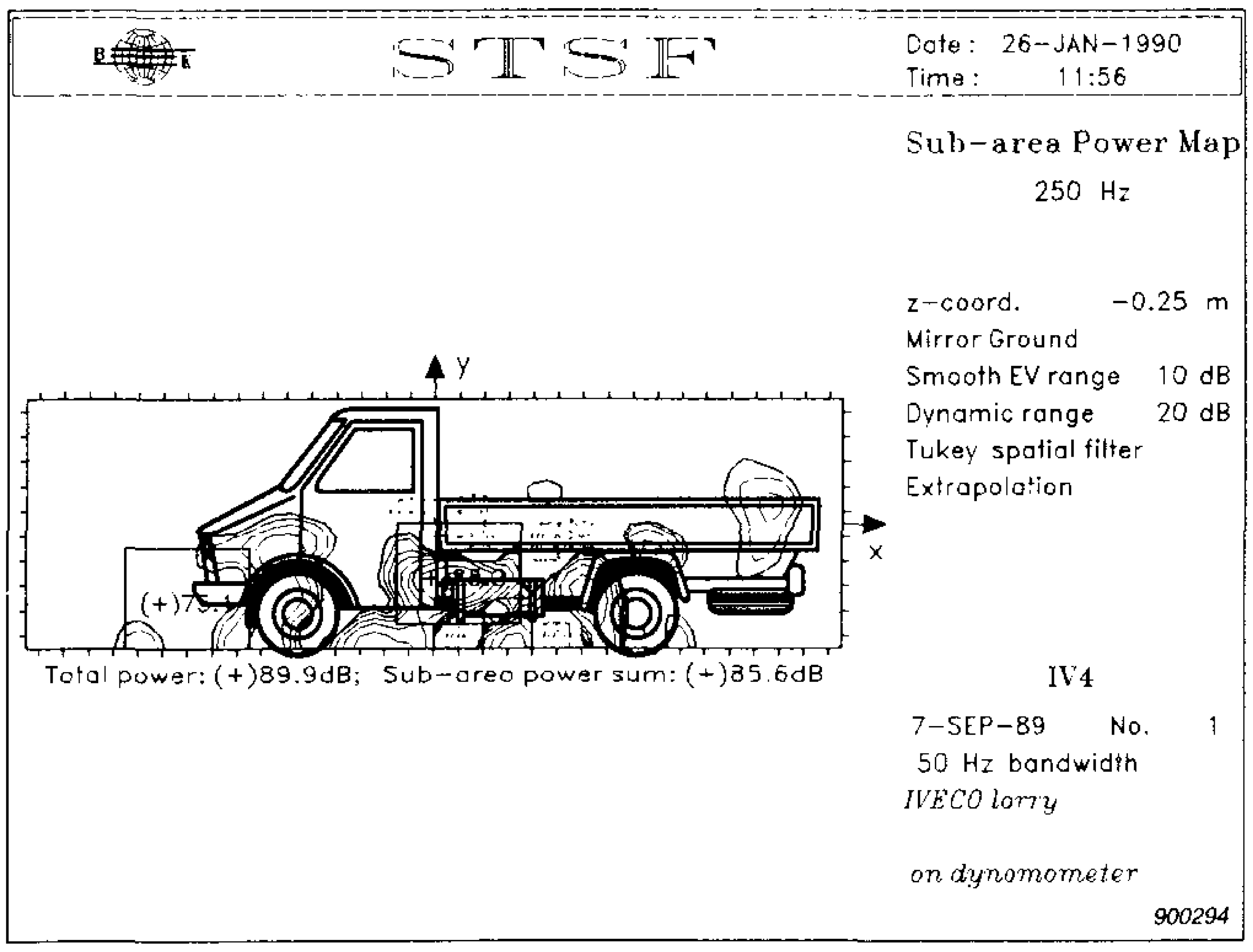

Fig. 28. Sub-area power map 250 Hz

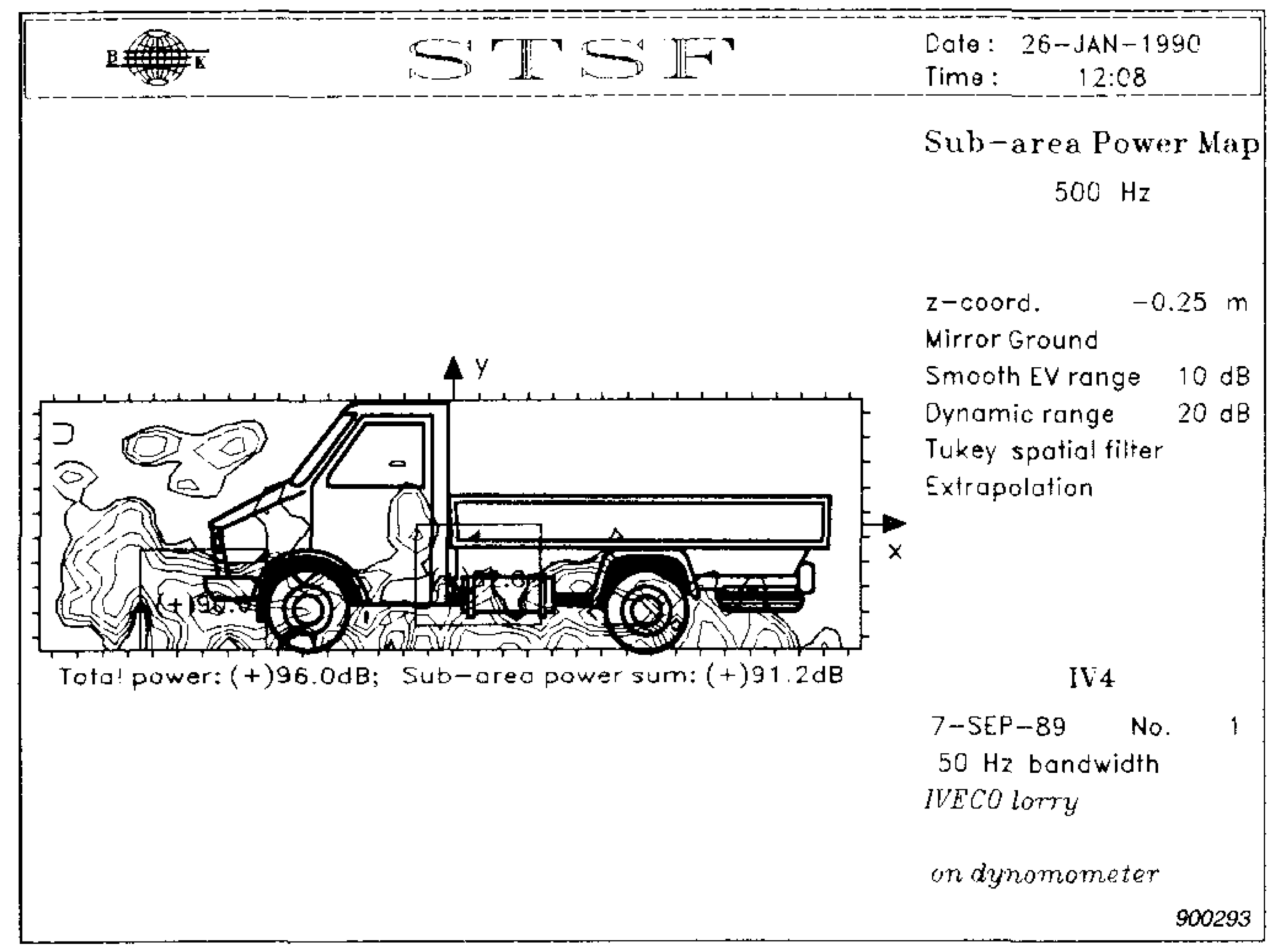

Fig. 29. Sub-area power map 500 Hz

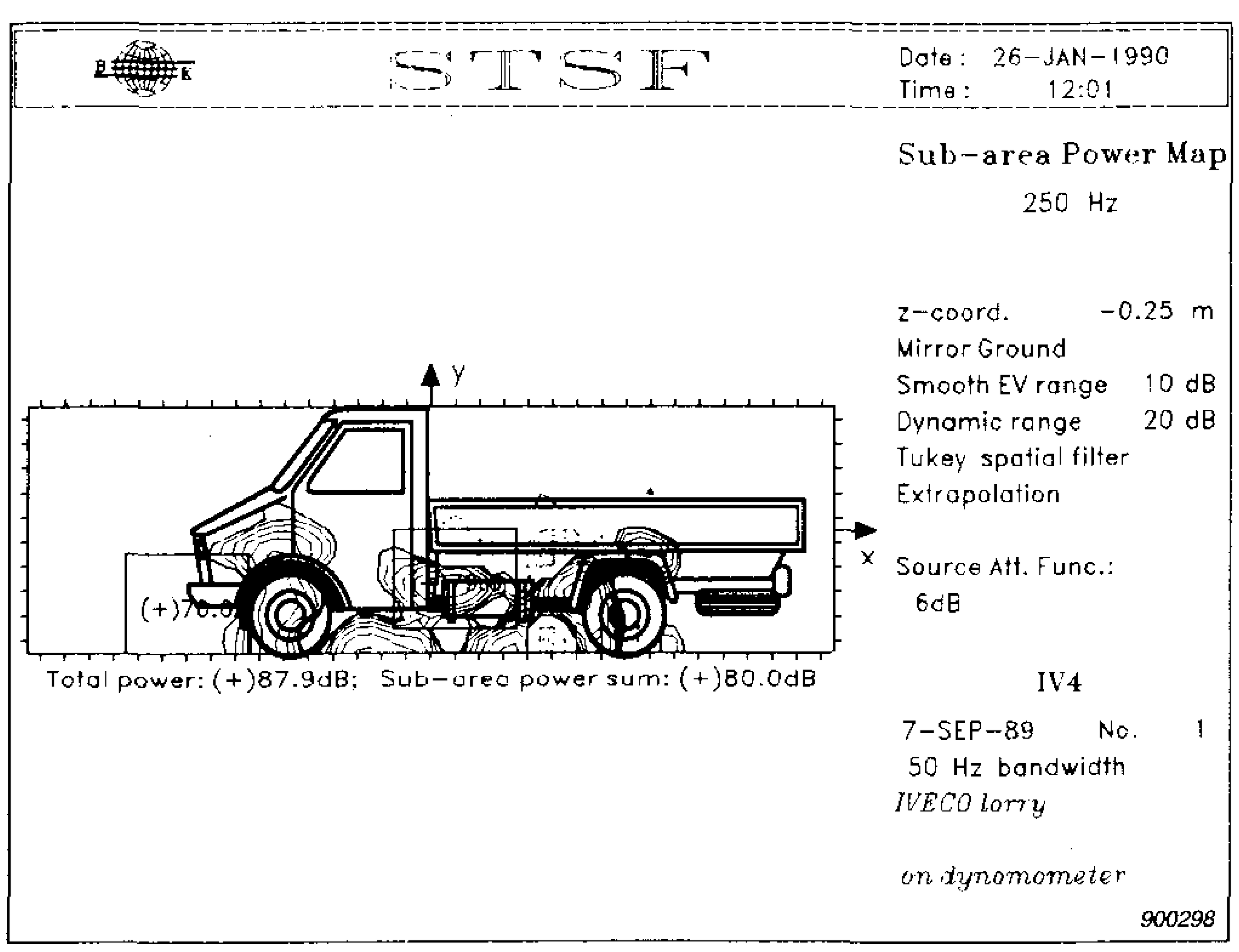

Fig. 30. Attenuation applied to power map at 250 Hz

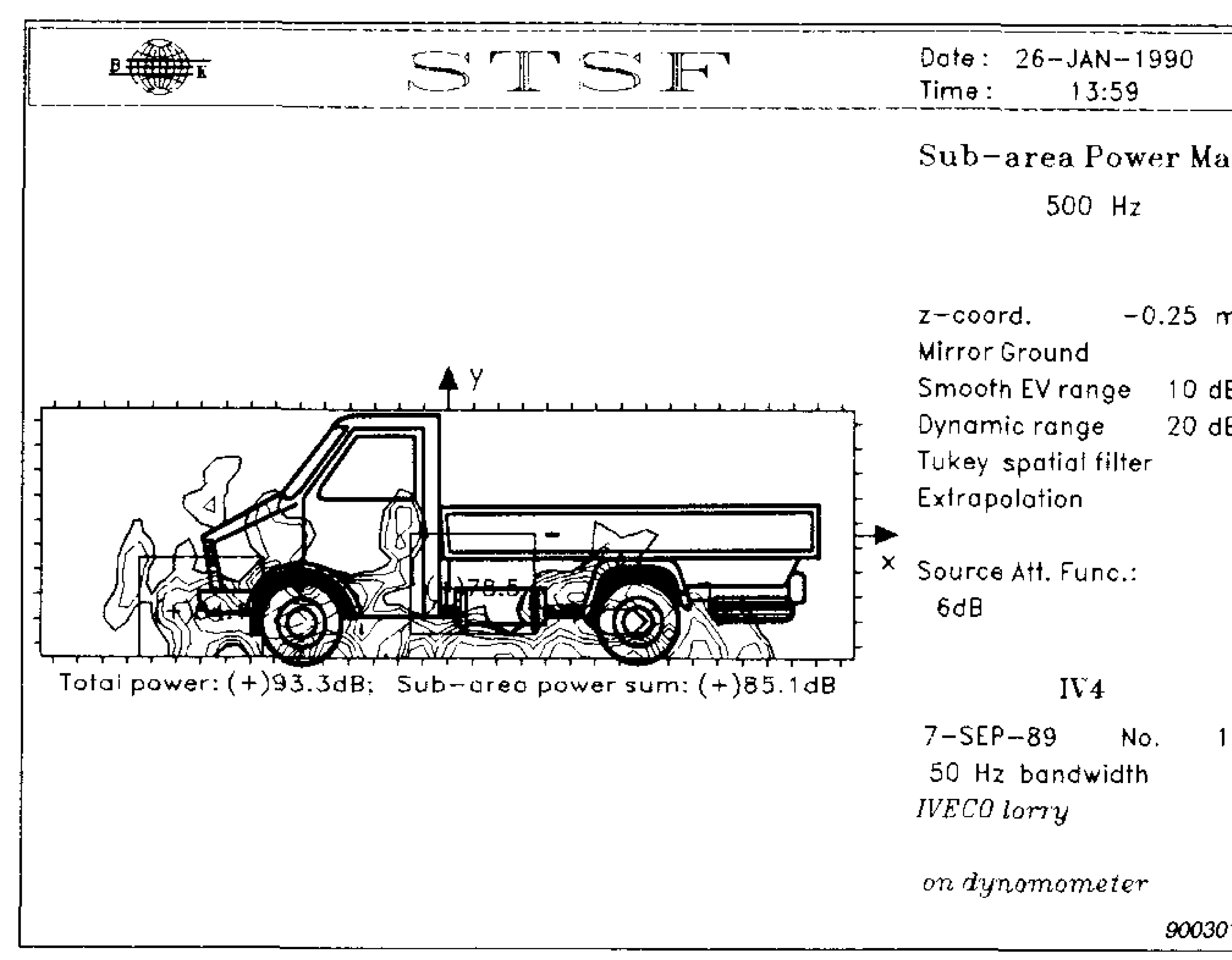

Fig. 31. Attenuation applied to power map at 500 Hz

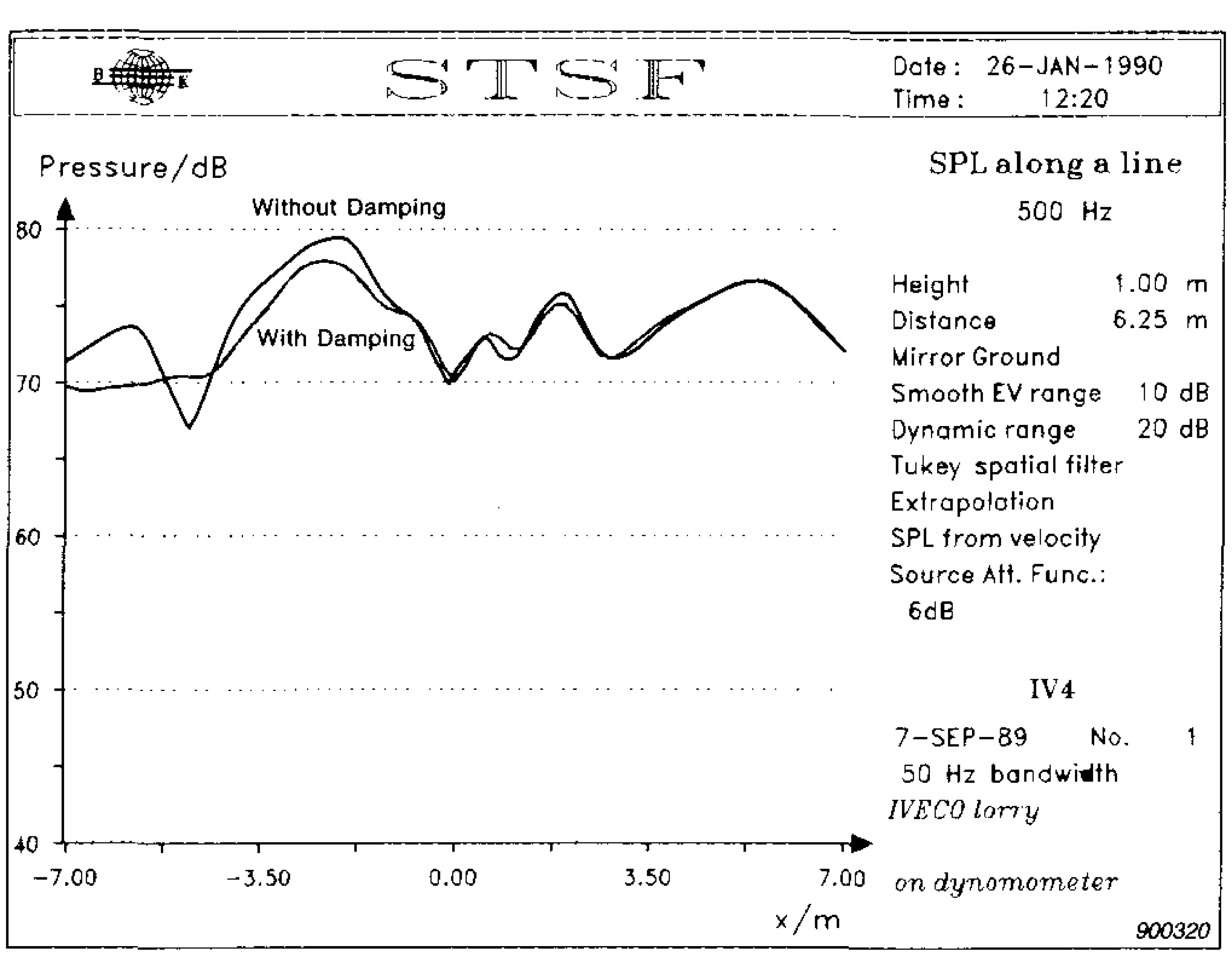

Fig. 32. Sound pressure level along a line at 7,5 m from the centre line of the vehicle with and without attenuation at 500 Hz

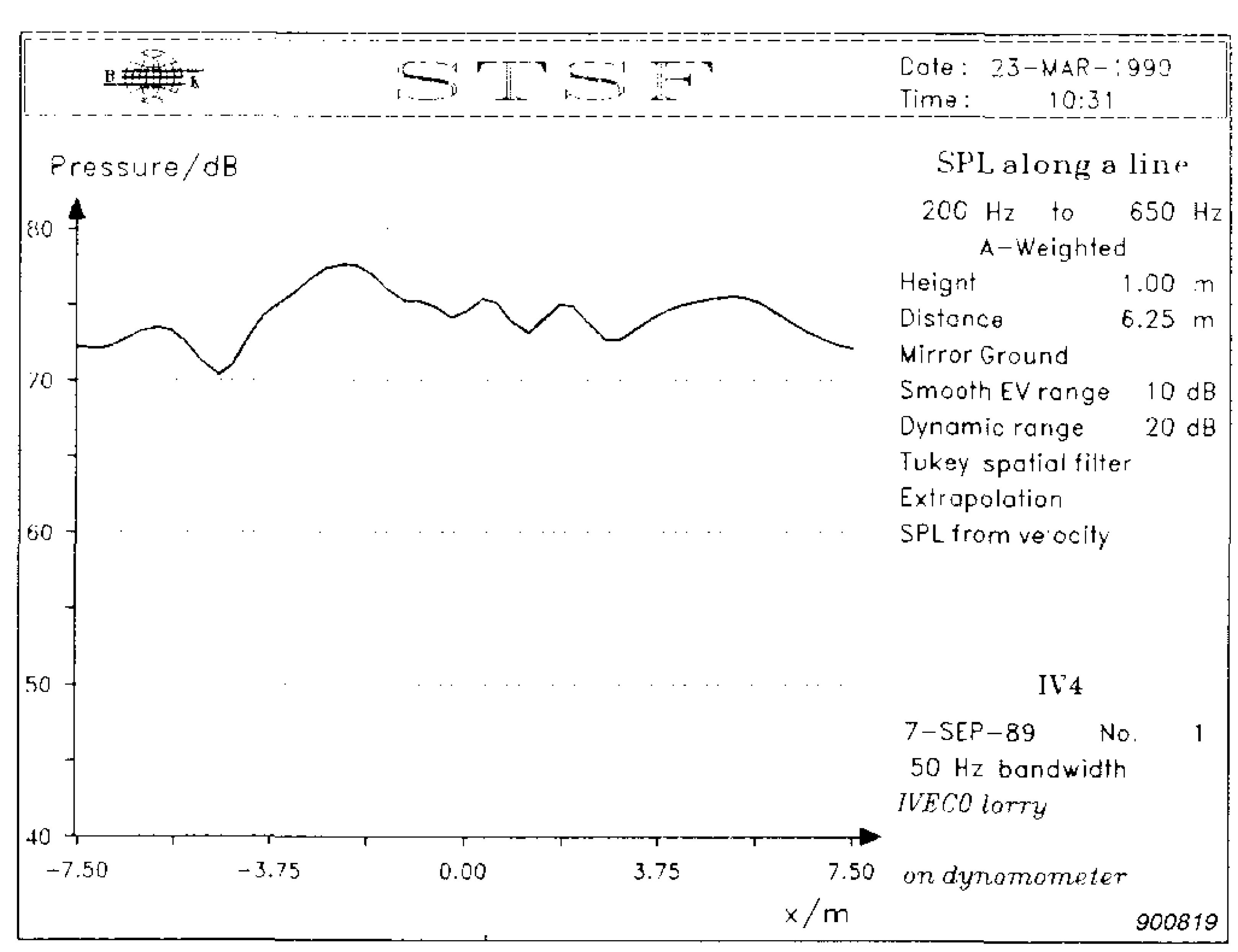

Fig. 33. Sound pressure level along a line at 7,5 m from the centre line of the vehicle A-weighted in the frequency range 200 Hz to 650 Hz

Conclusion

In the engine test cell the STSF system performed automatic, repeatable measurements on a diesel engine under various load conditions. Much more information was obtained using the STSF technique than with the more commonly used intensity technique. The measurements were relatively rapid (1,5 h to 3 h) compared to the time taken for traditional intensity measurements (4 h to 6 h) and the time taken to install the engine (up to 3 days for a new type of engine).

The measurements made in the dynamometer test cell were not performed under ideal circumstances (e.g. background noise from cooling fan, small room with many reflections, removing then repositioning of the vehicle on the dynamometer during the measurement). The total disturbance on the results was not too detrimental. More importantly, the disturbance could be shown by means of the validation procedure so that the engineer could decide whether to continue or re-configure the test set-up. Good visualization of the sound field was obtained and the results compared favourably with those from an external test site.

The results provided complete descriptions of the sound fields in particular:

- ○ Sound power
- ○ Pressure, active intensity, reactive intensity and particle velocity distributions in various representations
- ○ Ranking of noise sources

For both measurements the system enabled theoretical changes to be made to the field to provide predicted noise levels.

Acknowledgements

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C. Mazzoni, Ing. Vipiana, Sr. Furvis, D. Ghiradi & R. Figliuolo.

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