inter.noise 2004
Prague • Czech Republic • August 22–25

The 33rd International Congress and Exposition
on Noise Control Engineering

The acoustics of public squares/places: a comparison between results from a computer simulation program and measurements in situ

Dario Paini[a,b], Jens Holger Rindel[a], Anders Christian Gade[a], Giuseppe Turchini[b]

[a] Acoustic Technology, Ørsted-DTU, Technical University of Denmark
[b] Politecnico di Milano, Italy (BEST, Building Environment Sciences and Technology)

dario.paini@polimi.it;
[dp;jhr;acg]@oersted.dtu.dk; giuseppe.turchini@polimi.it

Abstract [176] In the context of a PhD thesis, in which the main purpose is to analyse the importance of the public square/place ("agora") as a meeting point of sound and music, with particular regard to its use for concerts (amplified or not), a first step was done, making comparisons between measurement in situ and results coming from a computer simulation program (Odeon), usually used for enclosed places, such as theatres, concert halls, etc. The main objective of this paper is to study how accurate such a program is for analysis of this kind of open spaces, which could have a regular or a complex shape, and which is not completely closed and not completely open, with highly reflecting and partially diffusing vertical surfaces (the facades) and with one totally absorbing surface (the sky). A natural application of these results will be the possibility to detect the best position for a sound source (typically an orchestra or a band during, for instance, music summer festivals) and the best position for the audience. A further result could be to propose some acoustic adjustments to achieve better acoustic quality by considering the acoustic parameters which are typically used for concert halls and opera houses.

1 INTRODUCTION

When considering theatres or concert halls, acoustical characteristics are usually well-known: we have a lot of experience and data from halls, and most of them are for a well specified range of music and speech performances.
Public squares, instead, are used for any kind of music (jazz, rock, classical, etc.) or (political) speech (especially during summer periods), but the acoustical implications of such sites are almost never considered, so that it's not uncommon to listen to a concert in a place where that music does not sound as desired, or to hear a classical concert in the same place where few days before an amplified concert was played. Rock amplified concerts, for instance, need short reverberation time (0,6–1sec. [5]). Flutter echoes and low intelligibility are some of the effects caused by not considering the acoustical characteristics of the place.
The aim of this paper is to compare results coming from impulse response measurements in a selected public square in Copenhagen, and results from a simulation run with a room acoustic model. Further analyses are then made using the model to predict consequences coming from changes in the square.

1.1 Choice of the Public Square for the measurements

Different parameters were considered in order to choose the square which had the better characteristics for the measurements: shape of the square, dimensions, materials of the façades/ floor, presence (or not) of lateral streets, height of the façades, presence (or not) of vegetation, habit to play concerts inside the square during summertime, etc. In order to have better results, measurements should have to be held within an acceptable (low) background noise level. It was soon clear that this was the main problem in a lot of public squares: noise from traffic, works in progress, many tourists passing by and talking, fountains, alarms, church bells, birds singing, etc.
Finally a solution was found with the internal square of the Industrial Design Museum in Copenhagen (Kunst Industri Museet – Grønnegården). The Leq (A) of the background noise was 48 dBA (see Figure 1). The only noises were from birds (above 4-8 kHz), some works in progress from a street close to the square (only during certain periods of the day), and some traffic noise (at low frequencies). The SNR was acceptable at almost all the frequency bands, even if with some problems at low frequencies (see further).
The place is a rectangular shaped area of 84x60m; the height of the façades vary from 4.1m to 9.2m (see Figure 2). The roof is sloping with an angle of 39°; the irregular surface can cause a scattering effect especially at high frequencies. The "floor" is basically made of grass. Trees are distributed in a regular way in the square.

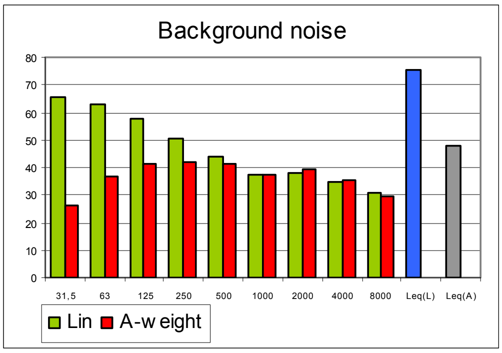


Figure 1 – Background noise during the measurements

2 MEASUREMENTS

Measurements were done during a cloudy day: temperature was 10°C, relative humidity at 70-80%, wind speed 3-4 m/s.

2.1 Choice of the position of the sound source and receivers

The sound source is represented by an omnidirectional dodecahedron loudspeaker (height = 1.5m), which was positioned in two points in the square, in an area where usually the orchestra is located during the concerts. The lower limit of the loudspeaker was 125Hz, which yielded to not consider the measurement down to this frequency band. The trees mainly form two double rows (see Figure 3) distributed parallel to the lateral façades at 13-16m, so that the audience can just take place in the central part of the square: only the central area was considered for selecting the 7 receivers positions (omnidirectional microphone, height =1.3m); the chosen positions can be seen in the Figure 3.
The software "Dirac" was used, with an e-sweep of 10.9sec. In principle a larger length would have been used to increase the accuracy of the measurement, but the longer the signal, the higher the possibility of encountering external noises (such as airplanes, birds, church bells): 10.9 sec. seemed to be a good compromise.

The following acoustics parameters were measured: reverberation parameters (EDT, T10, T20, and T30), energy ratios (C_{80}, D_{50}), and intelligibility parameters (STI male/female).

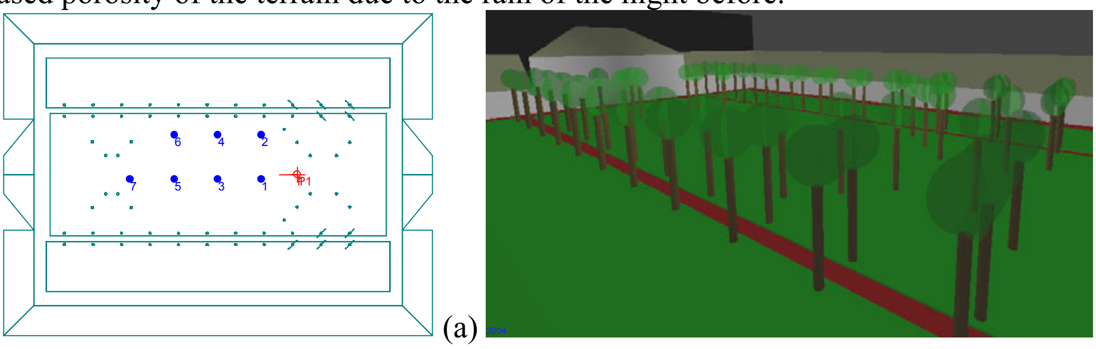
Figure 2 – Kunst Industri Museet – Grønnegården

3 SIMULATION WITH ODEON

ODEON is PC software used for simulation of interior acoustics of buildings. It uses prediction algorithms based on image-source method combined with ray tracing. and it's usually used for the prediction of acoustics in large rooms such as concert halls, opera halls, auditoria, etc.

3.1 Choice of the materials

The choice of the materials is very important in order to have accurate results to be compared with measurements. It had rained before the measurement so that we had to take into account on this variation on Odeon simulation when selecting the appropriate absorbing coefficients.
The façades are made basically of concrete walls and windows (glass and wooden frames). The surface represented by windows (glass and wooden frame) was about 25% of the total. In order to have faster calculation without decreasing the quality of results, it seemed convenient to treat all the façades as unique mixed material made of the weighted contribution of each one (75%: concrete, 21,25%: glass, 3,75%: solid wood). Scattering effects coming from the irregularities of the original surface were taken into account, adding a scattering coefficient of 0,1 in the calculation model. A higher scattering index (0,7) was added to the roof of the buildings, due to its irregularities: this is good especially at mid-high frequencies. To calculate the absorbing coefficient of the grass the Delany and Bazley model was used, with a porosity σ = 100 kNsm^{-4}, to take into account the decreased porosity of the terrain due to the rain of the night before.



(a) (b)

Figure 3 (a) & (b) – (a) The model as drawn with Odeon. It's possible to see the source and receivers' positions, the distribution of the trees in the square etc. A black box surrounds the square: it a totally absorbing box which permits to have a completely closed volume. The upper face of the box is of course modeling the sky as well. (b) Overview of the modeled public square

The trees were modelled like a cylinder (the trunk), high reflecting at high and low frequencies, which a scattering index of 0,7, and two circles (perpendicular one to each other) which represent the beams. To get a more realistic behaviour of the model, they are considered 50% transparent with a scattering of 0,6. The "ceiling" of the square is represented by the sky which is totally absorbing at all frequencies.
A comparison among different acoustics parameters, usually used in evaluating the acoustics of theatres and concert halls, was done.
In order to compare simulation with the measured results, the error was defined as [2]:

$$Error = \frac{\left| AP_{measured} - AP_{simulated} \right|}{SL} \tag{1}$$

where:

$AP_{measured}$	is the measured value of the current acoustics parameter
$AP_{simulated}$	is the simulated value of the current acoustic parameter
SL	is a subjective limen for the current acoustic parameter (ex.: SL for T30 is 5% of the measured value [1])

The error is calculated for 4 classes of simulation, for each receiver point:

- 180.000 rays; TO[1]= 2
- 300.000 rays, TO = 1
- 300.000 rays – TO = 2
- 300.000 rays – TO = 2, with low scattering index (=0,2) on the roof of the building
- 500.000 rays – TO = 2, with low scattering index (=0,2) on the roof of the building

Low TO seems to increase the error. Using 180.000 rays (TO=2) gave the minimum errors at mid-high frequency band, while at low frequencies 300k or 500k rays (with low scattering of the roof) seem to be better, as shown in the next figure from R5). For further analysis, data from 180.000 rays (TO=2) will be used.

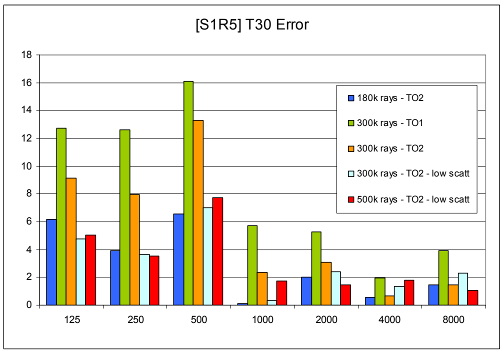


Figure 4 – T30 - Comparison of error in SL-units, with different calculation parameters

The first parameter that was compared was reverberation time (T30), which can be considered one of the main factors "governing most aspects of overall room acoustics as heard by the audience" [3]. As reverberation time is not usually position dependant, average and standard deviation from each receiver point were calculated (for each frequency band), both for the measured and for the simulated values. Results (Figure 5) state that the accuracy of the simulation is good if compared with the measured averaged values; low values of standard deviation from 250 up to 8k Hz mean that there aren't great variations of T30 among the receivers' positions. The quite high value of

[1] Below the transition order, calculations are carried out using the "Image Source Method", above the transition a special ray-tracing algorithm is used (from Odeon Manual)

standard deviation at 125Hz, for measured data can be attributed to low SNR during measurements (see par. 1.1).

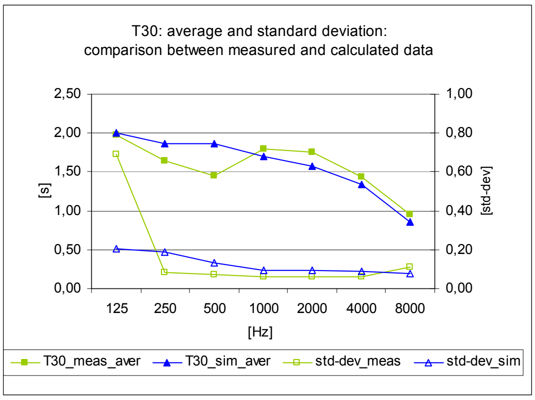
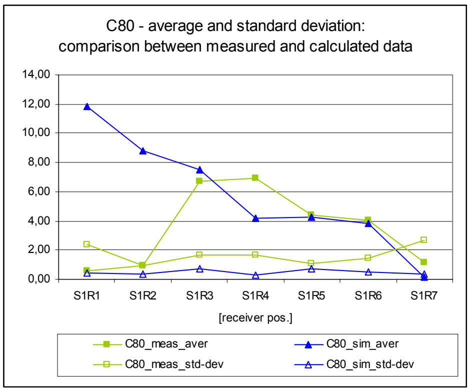


Figure 5 – T30: comparison between the simulated and the measured data of average and standard deviation

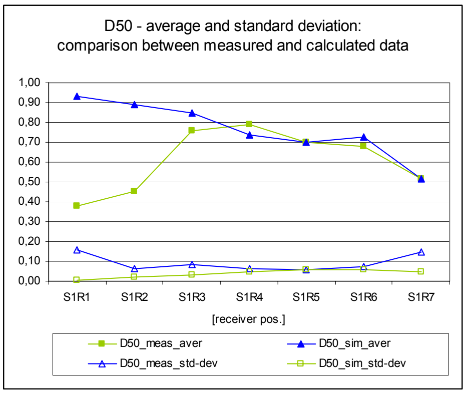
Clarity index C_{80} and Definition D_{50} are not so much frequency dependant, while they rather vary with the distance of the receiver from the source; for this reason average was calculated as:

$$\overline{AP} = \frac{1}{\#\,of\ \ freq.\ bands} \cdot \sum_f (AP)_f \tag{2}$$

where AP stands for the acoustic parameter (C_{80} and D_{50}), f is the frequency band considered (250 - 2kHz).



(a)



(b)

Figure 6 – (a) 'C_{80}' – (b) 'D_{50}': comparison between the simulated and the measured data at different receiver points, of average and standard deviation (frequency range: 250-2kHz, octave band)

S1R1	S1R2	S1R3	S1R4	S1R5	S1R6	S1R7
8,0	12,0	18,0	20,1	28,0	29,4	38,0

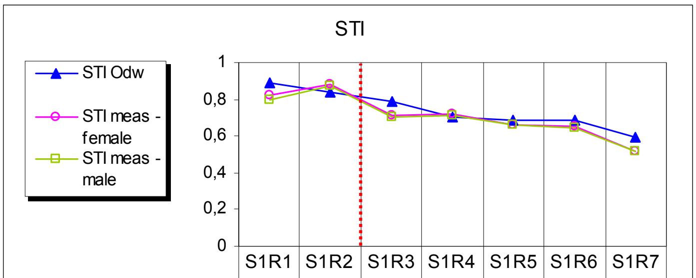
Table 1– Distances, in meters, from the source (S1) to the receivers (Rn)

For both indexes the simulated values and the measured ones don't fit so much at distances very closed to the source (S1R1-R2). In any case it's interesting to consider the decreasing of C_{80} and D_{50} with distance from the source.

The *STI* (Speech Intelligibility Index) was compared, as well, giving very good results at each receiver point, as shown in Figure 7, from which it's interesting to see the decreasing of STI as a function of the distance from the source. The critical distance[2] was calculated to be approximately 14,4m (at 2kHz), which means that below this distance the direct sound is higher than the

[2] The "critical distance" is defined as the distance from the sound source at which the direct and reflected sound energies are equal. Above this distance the overall sound pressure level is constant in the room in the form of a "diffuse sound field". A very reverberant room has a short critical distance.

reverberant one (which is the case of receivers R1 and R2), with respect of source position S1: STI_{R1} and STI_{R2} are very high for that reason, and above the critical path (R3 to R7) the acoustic of the square affects the speech intelligibility index. STI is affected by RT and background noise. During the simulation no background noise was added, and usually, during a measurement the SNR is to be acceptable to have good accuracy. During our measurement, anyway, some non-stationary noises (like airplanes, birds, etc.) were present during some of the measurements. This is why the STI simulated by Odeon is almost always higher than the one measured by Dirac.



	S1R1	S1R2	S1R3	S1R4	S1R5	S1R6	S1R7
STI Odw	0,89	0,84	0,79	0,70	0,69	0,69	0,59
STI meas - female	0,82	0,88	0,71	0,72	0,66	0,65	0,52
STI meas - male	0,80	0,87	0,70	0,71	0,66	0,64	0,52

Figure 7 – STI comparison between the simulated and the measured data at each receiver position. The receivers on the left of the red dashed line are positioned within the critical distance, while the ones on the right are positioned beyond it.

4 FURTHER ANALYSIS

As all the simulated acoustic parameters are fitting well (especially at mid-high frequencies) if compared with the measured ones, some further analysis can be done.

4.1 Auralisation

Auralisation was done in order to hear the effect of the square with different kinds of music.
Different sample were considered: for classical music, if not amplified, the main problem is the propagation of sound toward the rear part of the audience, as no reflectors are present. On the other hand the main problem for speech and amplified rock or jazz concerts is represented by flutter echoes, perceivable also just clapping hands in the “real” site.

4.2 Analysis of the impulse response with and without trees

To analyze the importance of trees in scattering sound, and so avoiding some effects of flutter echoes, or to increase the clarity C_{80} and the speech transmission index, a new simulation was done taking away trees from the model, and looking at the impulse response (Figure 8-b).
Reflections come mainly from frontal/rear and side façades. If they come from the wall in front of the audience, then the angle of incidence is about 0°; for such a case the following formula can be used [4]:

$$\Delta L \approx -0{,}6 \cdot t_0 - 8 \ \text{[dB]} \tag{3}$$

which gives the threshold of absolute perceptibility, and tells that if the delay (in milliseconds) between the direct and the first reflection is t_0, then the reflected sound is still audible as a distinct sound (flutter echo) even when the difference $L_{direct} - L_{reflected}$ is ΔL.
In both cases (a) and (b) the frontal reflection is heard at 0,318s, which means 143ms after the direct sound. This leads to ΔL=-93,8dB. In Figure 8 level are expressed in p(%): the direct and the

reflected sound are respectively 100% and 21%, so that $\Delta L=10*\mathrm{Log}(0{,}21^2)=-13{,}5\mathrm{dB}$: this sound is perceived as a flutter echo.

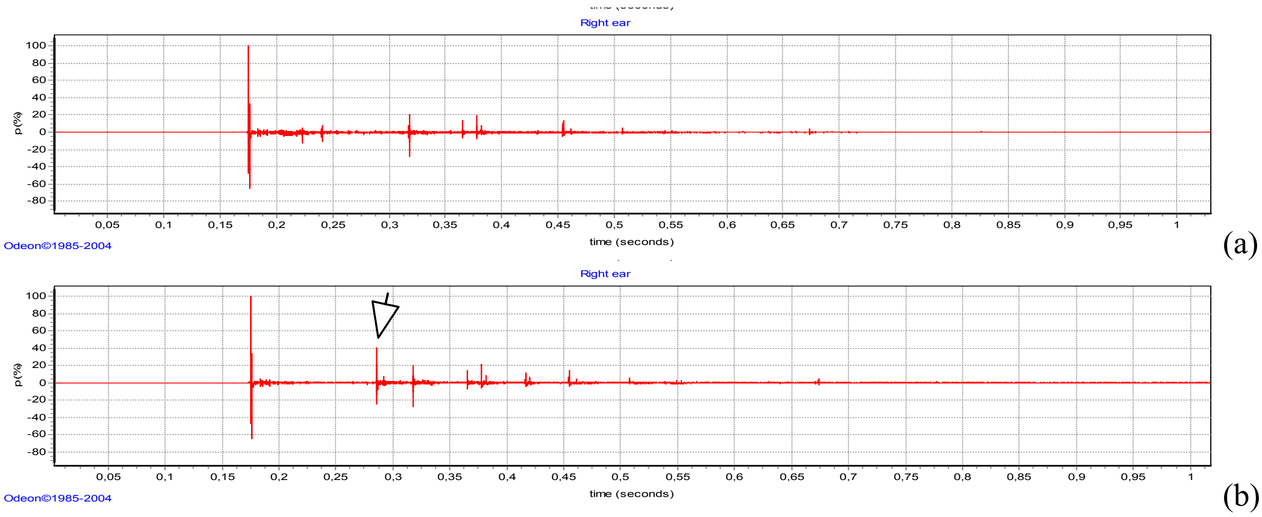


Figure 8 – Impulse response – [receiver position: R5] comparison between the impulse responses coming from the Odeon simulation, run with (a) and without (b) the trees. In (a), after the direct sound there are many weak reflections which come from the trees, which can improve clarity, D_{50} and STI. In (b), instead, after the direct sound, such reflections are hardly seen: a flutter echo is “added” at 0,291s.

Same computation can be done for the case (b) “without trees”; the new reflection which is added at 0,291s could be perceived as a flutter echo, for the same reason explained before.
Putting more trees could be a solution in such a situation, to avoid flutter echoes.
The same can be seen in Figure 9, which is a 3D-billiard simulation; it can be used for investigating or demonstrating effects such as scattering effects, flutter echoes or coupling effects. A number of billiard balls are emitted from the source and reflected by the surfaces in the room.
It can be demonstrated that trees can increase the level of C_{80}, D_{50} and STI.

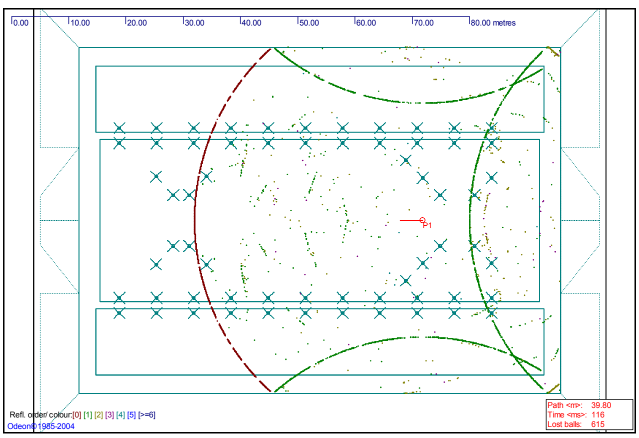


Figure 9 – “3D-billiard simulation” - contributions of the trees (at mid-high frequency) on sound propagation from an omnidirectional source. Without the trees we shouldn’t have all the scattered sounds (isolated billiard balls in the centre of the square). Presence of trees can reduce the possibility of flutter echoes. Different colors mean different reflection orders.

4.3 Lateral Energy Fraction

Values of LEF, in large concert halls may vary between 0 and 0.5 [4]. This index can be calculated either by Odeon or by the formula:

$$LEF = 0{,}39 - 0{,}0061 \cdot Width \quad (4)$$

Both Odeon and the formula give the value of about 0,024, especially at high distances from the source.

4.4 Statistical Reverberation Time: a Quick Estimation

When organizing a concert in a public square, a quick estimation of the RT could be useful to realize how the concert will sound.
The calculation of error was done, taking into account the RT formula by Sabine, Eyring and Arau-Puchades. Despite the assumption for Sabine RT formulae is that the sound field is diffuse (all surfaces have the same absorption properties, no de-coupling effects, etc.) it came out that this is the most accurate, even if the error is quite large. Hence, a good way of calculating an accurate RT could be:

$$RT_{sabine\_corr} = \frac{RT_{sabine}}{C} \quad (5)$$

where RT_{sabine_corr} is the 'real' RT
$C=RT_{sabine}/RT_{measured}$ is a correction and, in our comparisons, it's usually 0,7-0,8 ($RT_{sabine}<RT_{measured}$) at mid-high frequencies
$RT_{measured}$ is the RT measured in a receiver point in which the distance source-receiver is higher than the critical distance.

5 CONCLUSION

Comparisons between different types of data were done: measured versus simulated acoustics parameters, statistical reverberation times versus measured, impulse response with and without trees. Further analysis like the calculation of spaciousness was done. The comparison describes a good agreement with the measured parameters.
Making simulation with accurate software is a good way of considering and solving acoustical problems such as the ones encountered in this paper.

ACKNOWLEDGEMENTS

The Authors would like to thank Thomas Bakke and everyone at Kunst Industri Museet for their kind support during the measurements, and everyone at the DTU – Acoustic Technology, especially: Claus Lynge Christensen, Jørgen Rasmussen, Bruno Fazenda, Martin Lisa Nielsen, Hiroshi Onaga and Jingjing Xu.

REFERENCES

[1] Ingolf Bork – A Comparison Of Room Simulation Software – The 2nd Round Robin On Room Acoustical Computer Simulation" – Acta Acustica, 2000 (pp.943-956)
[2] C. A. Weitze, C.L. Christensen, J. H. Rindel, A.C. Gade - "Computer Simulation of the Acoustics of Mosques and Byzantine Churches" – 17th ICA (International Congress on Acoustics), 2001
[3] Leo Beranek – Concert and Opera Halls - How they sound (p. 46) – Acoustical Society of America, 1996
[4] Heinrich Kuttruff – Room Acoustics . 4th Edition (Spon Press), 2000
[5] N. Werner Larsen, E. Olmos, A.C. Gade "Acoustics in halls for rock music" – Joint Baltic-Nordic Acoustics Meeting 2004 – 8-10 June 2004, Mariehamm, Åland