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Southeast Alaska Cruise Ship Underwater Acoustic Noise

by
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Underwater acoustic signatures of six cruise ships that sail Southeast Alaska.

Measured at Southeast Alaska Acoustic Measurement Facility (SEAFAC) in September 2000 and June 2001.

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ABSTRACT

Between September 2000 and June 2001, the underwater radiated noise levels for six Southeast Alaska cruise ships were measured at the U.S. Navy's Southeast Alaska Acoustic Measurement Facility near Ketchikan, Alaska. The primary objective of this project was to quantify noise levels typical of large cruise ships common to Southeast Alaska. This group of ships included diesel-electric, direct-diesel, and steam turbine propulsion plant ships ranging in size from 23 to 77 thousand gross tons and from 617 to 856 feet in length. Ten-knot overall sound levels ranged from 175 to 185 dB relative to 1 microPascal at 1 yard with the highest one-third octave band level at 182 dB. The 10-knot sound level for the steam turbine ship was the lowest among the ships tested, but no ship was clearly the loudest or quietest at all frequencies.

Propulsion system type and cavitation performance were important factors in cruise ship noise character. Diesel-electric ship noise signatures were dominated by noise energy from diesel generators and from electric propulsion motors in combination with frequency converters and diesel generators. Propulsion diesel and reduction gear noise were important contributors in the direct-diesel ship's signatures. Turbine generator, propulsion turbine, and reduction gear noise were the most significant noise items in the steam plant ship's signatures.

Each ship was tested at two speeds. The sound levels of two ships were strongly speed dependent while others exhibited less speed dependence. Differences in noise levels between speeds were typically due to changes in propulsion and cavitation noise contributions. This investigation indicates that a 10-knot ship speed limit in Glacier Bay (versus 20 knots) would, in general, result in reduced underwater noise levels, although the results also indicate there could be exceptions, particularly at speeds in the neighborhood of 15 knots. Only two ships were tested at speeds near 20 knots.

Ship noise levels were measured at a range of 500 yards from each ship and were projected to 1 yard and 100 yards to examine the effect of range on perceived noise level. This factor was significant in terms of ranking importance of noise sources, ranking noise levels by ship, and in the degree of noise level dependence on ship speed. Comparison of noise levels at these ranges indicated that mid-frequency noise energy would typically be more important than low frequency energy at ¼ mile.

NOTE ON RELEASE OF INFORMATION

Naval Surface Warfare Center agreed with the cruise ship companies represented in this report not to release cruise ship noise level information without permission. The cruise lines granted permission for release of this information to the National Park Service. Further distribution of specific cruise ship information contained in this report should only be accomplished with cruise line permission.

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PROJECT DESCRIPTION

On 5 September 1999 the first of several cruise ships entered Behm Canal near Ketchikan, Alaska to have its underwater noise levels measured. Later that month, four additional cruise ships repeated this process, and in June 2001 a sixth ship was tested. Each of these ships regularly conducted Southeast Alaska tour cruises, including cruise time in Glacier Bay National Park and Preserve. The individual cruise ship companies, Glacier Bay National Park and Preserve, and Naval Surface Warfare Center Detachment Bremerton (NSWC DET Bremerton) were involved in the project. Funding for the testing was provided to NSWC DET Bremerton by each of the cruise ship companies. The National Park Service provided funding to compile the results of the testing into a single report. The noise measurements were conducted by NSWC DET Bremerton at the Southeast Alaska Acoustic Measurement Facility (SEAFAC), Fig. 1. SEAFAC was established by the U.S. Navy near Ketchikan, Alaska to measure the underwater noise signatures of ships and submarines.

The goal of this project was to quantify the underwater noise levels associated with cruise ships of the type that typically operate in the waters of Glacier Bay National Park and Preserve. Establishing these noise levels constituted the first step in assessing the effect of cruise ship operations on Glacier Bay's underwater noise environment. The content of this report is focused on reporting cruise ship noise levels and noise sources. The overall effect of cruise ship operation on Glacier Bay's underwater acoustics is not discussed in this report.

The cruise ship companies that participated in the project were Crystal Cruises, Holland America Line, Norwegian Cruise Line, Princess Cruise Line, and World Explorer Cruises. Ships ranged in size from 23 to 77 thousand gross tons and from 617 to 856 feet in length. The oldest ship was launched in 1958, the newest in 1999. Steam turbine, direct diesel, and diesel-electric propulsion plant types were represented among the ships that were evaluated. Pertinent specifications for each ship are listed in Table 1. More detailed information on each ship's equipment is provided in Appendix A. All of the cruise ships that were tested are pictured in Fig. 2.

Table 1 – Cruise Ship Specifications

Ship	Displacement (thousand tons gross)	Length (ft)	Propulsion Type	Launched	Date Tested at SEAFAC
Crystal Harmony	49	790	Diesel-Electric	1995	5 Sep 1999
Holland America Statendam	55	720	Diesel-Electric	1993	7 Sep 1999
Universe Explorer	23	617	Steam Turbine	1958	8 Sep 1999
Dawn Princess	77	856	Diesel-Electric	1997	9 Sep 1999
Norwegian Wind	50	754	Direct Diesel	1998	18 Sep 1999
Norwegian Sky	77	853	Diesel-Electric	1999	29 Jun 2001

Each cruise ship was tested at two different speeds: 10 knots, and a second speed of the cruise ship company's choosing. Table 2 lists the test speeds for each ship. Ship speed over ground was established by SEAFAC's radar based tracking system. If a given ship was equipped with variable pitch propellers, the ship determined the shaft rpm and propeller pitch setting combination that it would use for testing at its two test speeds. Additional information regarding propulsion rpm, pitch settings, etc. for each ship is provided in Appendix B. Noise signatures were only established for constant speed, straight-line operating conditions for all of the ships. Because of the limited scope of this project, no additional operating conditions, including thruster operations, were evaluated.

Table 2 - Cruise Ship Test Speeds

Ship	Primary Test Speed (kt)	Second Test Speed (kt)
Crystal Harmony	10.5	15.3
Holland America Statendam	10.8	18.0
Universe Explorer	10.0	15.5
Dawn Princess	9.9	5.6
Norwegian Wind	10.0	19.2
Norwegian Sky	10.8	14.2

NOISE MEASUREMENT APPROACH

Cruise ship noise signatures were measured while the ship under test passed 500 yards to the west of SEAFAC's western acoustic measurement array on a courseline parallel to the SEAFAC range centerline. The noise levels given in this report represent *beam aspect* levels. To obtain beam aspect noise signatures, noise levels were averaged over a sector starting at 200 yards prior to CPA to 200 yards after CPA, as shown in Fig. 3. At least two passes by the noise measurement array were conducted at each test speed.

The noise measurement hydrophones on the western array were located at depths of 200, 300, and 400 feet. The noise levels for each test were established by averaging the levels measured at each hydrophone. The noise signatures for each ship and speed were derived by averaging the results from all of the tests conducted at that speed. The water depth at SEAFAC near the measurement array was approximately 1200 feet.

Primarily this report presents cruise ship noise levels as 1-yard source levels. These signatures represent *far-field* noise levels translated to 1 yard from the cruise ship. These levels were inferred from the levels measured at 500 yards. The 1-yard levels given in this report may be treated as source levels, i.e. they are not dependent on the location where they were measured. If appropriate measures are taken to model the noise propagation characteristics of a specific area of interest, they can be used as a "starting point" to project noise levels that would be experienced at any location in that area.

Some discussion is also given to 100-yard and 500-yard noise levels. The 100-yard distance was used because some regulatory bodies prohibit vessels from approaching to within 100 yards of marine mammals. Glacier Bay National Park and Preserve requires vessels to maintain a separation of ¼ nautical mile, or 500 yards, from marine mammals. The 500-yard noise spectra for each ship are given in Appendix D.

Since little is known regarding the directivity of cruise ship noise, and since off-beam aspect noise levels were not measured, no attempt was made to infer noise levels at aspects other than those measured on the beam. As a result, this report contains no discussion of bow and stern aspect noise levels.

DISCUSSION OF NOISE SPECTRUM

Often when noise levels are reported, it is common to quote them in terms of a single number. For example, the noise level from operation of heavy construction equipment may be reported as 110 dB. Usually this number represents the sum of all of the noise energy that occurs within the frequency range of human hearing. However, if more information regarding the character of the noise source is desired, the sound level should be represented in spectral form. In this case the entire frequency range covered in the measurement is divided into smaller individual frequency bands and the level for each band is established.

Ship noise signatures are commonly represented in one-third octave spectrum form. This format shows the *distribution* of acoustic energy that is emitted by a ship over a wide frequency spectrum by plotting noise levels for each standard one-third octave band* in a level versus frequency format. This representation graphically demonstrates the amount of noise energy that is present at low, mid, and high frequencies, and serves as a tool to identify the predominant noise sources that make up a ship's total acoustic signature. An example of a one-third octave noise spectrum is shown in Fig. 5.

The noise spectrum representation is also useful as a noise source ranking tool. For example if a noise spectrum shows that high noise energies are present near 3 kHz, this result would be important to humans because human hearing is especially sensitive to noises that occur at frequencies near 3 kHz. On the other hand, significant noise energies at 100 Hz might be less important because human hearing sensitivity at this frequency is relatively low. Use of the noise spectrum instead of single numbers that represent total energy provides more information regarding the noise source itself and its potential effects on a creature exposed to that noise.

* One-third octave band center frequencies are established by assigning three frequency bands per octave in the frequency spectrum. For example, the step from 100 to 200 Hz represents one octave (an octave corresponds to a doubling in frequency). The one-third octave frequency bands between 100 and 200 Hz are 125, 160, and 200 Hz.

To supplement the approach described above, limited *narrowband frequency analysis* was also used to identify machinery noise sources that contributed to each ship's overall noise levels. Narrowband frequency analysis provides more detail of a noise source's frequency characteristics than one-third octave analysis because of its greater ability to resolve closely spaced frequency components. The results from this analysis are not discussed in detail in this report, but they were used to identify the sources of machinery-related noise components that are cited for each ship.

NOISE LEVELS IN WATER

When assessing the significance of underwater noise levels, it is important to recognize that in-water noise levels are measured on a different scale than in-air levels, and that they represent different sound intensities than in-air noise levels. This means that the sound intensity of a 100 dB noise in air is not equal to that of a 100 dB noise in water. In part, this effect is due to the use of different reference pressures in airborne acoustics versus underwater acoustics. This difference in scales is illustrated in Fig. 4, which shows a comparison between the underwater noise decibel scale and some familiar in-air decibel levels. Figure 4 demonstrates that the reader must resist the temptation to interpret underwater noise levels based on more familiar in-air decibel levels without accounting for the difference between the two scales. Appendix C contains additional discussion of in-air versus in-water noise decibel levels.

RESULTS

In this section the noise character of each ship is discussed with regard to noise level, frequency character, noise sources, and speed dependence. The one-third octave noise spectra for each ship are presented for the speeds at which they were tested, and then all of the ships are presented together to show the range of noise levels that were measured. In addition, cruise ship noise levels are compared to other known sources of underwater noise, both natural and manmade. The effect of distance from the cruise ship on observed noise levels is also briefly discussed.

Noise sources

The noise characteristics, or noise signatures, of a given ship depend on the type of propulsion plant, auxiliary equipment, and propellers with which it is equipped. Typically propulsion plant noise is a significant contributor to a ship's overall signature, so propulsion plant type is an important factor. The cruise ships evaluated in this project were equipped with either diesel-electric, direct-diesel, or steam turbine propulsion systems, as detailed in Table 1.

The noise signatures of the diesel-electric ships typically contained energy from the diesel generators and from the electric propulsion motors in combination with the frequency converters*. The levels of electric propulsion motor noise energy, and the frequencies at which they occurred, varied by ship and with propulsion shaft rpm. This noise energy was typically due to inherent discontinuities in the frequency converter electrical power waveform and the response of the electric propulsion motor to that waveform. In some cases other electrical power components were also present.

For the direct diesel drive ship, where the propulsion shaft was driven by diesel engines through a reduction gear, typical propulsion noise contributors included the diesel engines and the reduction gears. Because diesel engine rpm varied according to propulsion demand, these signature components occurred at frequencies that depended upon ship's speed.

Propulsion turbines, turbine generators, and reduction gears were the dominant sources of propulsion system noise on the steam turbine equipped ship. Propulsion turbine and reduction gear related noise components also occurred at frequencies related to propulsion shaft rpm.

Cavitation**, when it occurs, produces substantial acoustic noise. It is often attributable to the propeller, but flow at specific locations on a ship's hull can also be a source of cavitation.

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* Electric propulsion plants use a frequency converter to convert the constant frequency AC power produced by the diesel generators to a variable frequency waveform required to drive the electric propulsion motors at a given rpm. Depending on the ship, this frequency converter may be called a synchroconverter or a cycloconverter.

** Cavitation occurs when local pressures in the flow field associated with a propeller or hull location drop to very low values. When sufficiently low pressures are reached, water flashes into water vapor and a small water vapor bubble is created. These bubbles expand and contract violently and produce intense acoustic pressures that typically result in significant noise levels.

The amount of cavitation produced by a given ship propeller depends on its propeller design, propeller condition, and the ship's speed. The pitch and rpm combination are also important, if the ship is equipped with a controllable pitch propeller. Optimum pitch and rpm combinations can be established for controllable pitch propellers that minimize propeller cavitation, however the best combination for cavitation might not be optimal with regard to other operational issues such as fuel economy or exhaust emissions.

For cavitation occurring at locations on a ship's hull, the speed of the ship, turning maneuvers, and hull form shapes can be important factors. Incidents of cavitation occurring at rudders, struts, and other hull locations are known to occur. This project did not attempt to localize the source of cavitation noise on a given cruise ship when it was observed, however in some cases it was clear that the propeller was the source.

Noise components from rotating auxiliary machinery and other shipboard equipment also contribute noise to a ship's overall signature, but usually at lower levels than the propulsion systems. Examples of noise-generating auxiliary equipment include: air conditioning plants; water, hydraulic, and oil pumps; motor generators; and ventilation fans. The mechanical condition of a given piece of equipment can be an important factor in its noisiness.

Diesel engine noise will be present in a ship's noise signature whether the ship is equipped with diesel engines for direct propulsion power or with diesel generators for diesel-electric propulsion. As discussed above, the diesel engine rpm, and hence the frequency characteristics, for the direct propulsion diesel will vary with ship's speed. On the other hand, for the diesel-electric system, the diesel generators operate at a constant rpm and therefore their noise characteristics are not dependent on ship's speed.

<u>Overall noise character of each ship</u>

Each cruise ship that was tested exhibited its own unique underwater noise character. The differences between noise signatures were typically due to differences between propulsion system types and the intensity of cavitation noise. Brief discussions of the most significant noise features and the general noise spectrum character for each ship are given below. In addition, the noise levels for an azipod diesel-electric cruise ship are given in Appendix E. This ship was not evaluated at SEAFAC as part of this project, but the levels are given for reference.

Crystal Harmony

Like three of the other ships that were evaluated, the Crystal Harmony was powered by a diesel-electric propulsion system. Four diesel engine driven generators provided all electrical service to the ship, including power to the electric main propulsion motors. The ship was equipped with a cycloconverter to convert constant frequency AC electrical power from the generators to variable frequency AC power to drive the electric propulsion motors.

Crystal Harmony's underwater noise levels for 10-knot operations are shown in Fig. 5 in one-third octave format with the most significant noise peaks labeled by source. Noise levels for 15 knots are compared to 10-knot levels in Fig. 6. These noise levels represent 1-yard source levels. Noise levels for 500-yard ranges are given in Appendix D.

Crystal Harmony's noise spectra were dominated by noise energy from the electric propulsion system and broadband cavitation noise. At 10 knots, components from the cycloconverters in combination with the electric propulsion motors were prominent at frequencies below 500 Hz and propeller cavitation was the dominant source of noise energy present at frequencies above 500 Hz.

As shown in Fig. 6, cavitation noise occurred at higher levels and over a wider frequency range at 15 knots. Cavitation noise levels were up to 14 dB higher at 15 knots and cavitation affected or controlled noise levels at frequencies above 250 Hz.

Additional discussion of Crystal Harmony's noise signatures may be found in NSWC DET's original report to Crystal Cruise Lines, ref. (2).

Holland America Statendam

The Holland America Statendam was powered by a diesel-electric propulsion system. Five diesel engine driven generators provided all electrical service to the ship, including power to the main propulsion motors. The ship was equipped with a cycloconverter to convert constant frequency AC electrical power from the generators to variable frequency AC power to drive the electric propulsion motors.

Statendam's 10-knot underwater noise levels are shown in Fig. 7 in one-third octave format. The most significant noise peaks are labeled by source. Noise levels for 18 knots are compared to 10-knot levels in Fig. 8. These noise levels represent 1-yard source levels. Noise levels for 500-yard ranges are given in Appendix D.

Statendam's 10-knot noise spectrum was dominated by diesel and propulsion noise, broadband cavitation noise, broadband noise from an unknown source, and a transient noise related to one of the propulsion shafts. The transient noise was only present over a small speed range around 10 knots and was related to the propeller pitch actuation system on the starboard propulsion shaft. It occurred at a rate of once per shaft revolution and with changes in speed of less than 1 knot, the noise vanished. Propeller cavitation was the dominant source of noise energy present at frequencies above 800 Hz. Noise from the electric propulsion system, diesel generators, and other equipment was present at frequencies below 100 Hz.

As shown in Fig. 8, cavitation noise occurred at higher levels and over a wider frequency range at 18 knots. At frequencies above about 250 Hz, cavitation caused noise levels to increase as much as 14 dB. The transient noise and the broadband noise from an unknown source that were both evident at 10 knots were not present at 18 knots.

Additional discussion of Statendam's noise signatures may be found in NSWC DET's original reports to Holland America Cruise Lines, refs. (3) and (4).

Universe Explorer

The Universe Explorer was powered by a fuel oil fired steam plant with three turbine generators for electrical service and two main propulsion turbines. Each propulsion turbine drove a propeller via reduction gears. Universe Explorer was the smallest and oldest ship, and the only ship with this propulsion type that was evaluated.

Figure 9 shows Universe Explorer's underwater noise levels for 10 knots in one-third octave format. The most significant noise peaks are labeled by source. Noise levels for 15 knots are compared to 10-knot levels in Fig. 10. These noise levels represent 1-yard source levels. Noise levels for 500-yard ranges are given in Appendix D.

Universe Explorer's 10-knot noise spectra were dominated by noise energy from the main reduction gears, the main propulsion turbines, the turbine generators, and broadband cavitation noise. Cavitation was the dominant source of noise energy present at frequencies above 800 Hz. At lower frequencies the highest-level noise energy was attributed to the turbine generators.

As shown in Fig. 10, cavitation noise occurred at levels up to 8 dB higher at 15 knots. More significantly, propulsion system noise, primarily from the main turbine and main reduction gears, increased up to 20 dB in isolated frequency bands compared to the 10-knot levels. The noise peaks from these components also shifted to higher frequencies at 15 knots.

Additional discussion of Universe Explorer's noise signatures may be found in NSWC DET's original reports to World Explorer Cruises, refs. (5) and (6).

Dawn Princess

The Dawn Princess was powered by a diesel-electric propulsion system. Four diesel generators provided all electrical service to the ship, including power to the main propulsion motors. The ship was equipped with a synchroconverter to convert constant frequency AC electrical power from the generators to variable frequency AC power to drive the electric propulsion motors.

Figure 11 shows Dawn Princess's underwater noise levels for 10 knots in one-third octave format. The most significant noise peaks are labeled by source. Noise levels for 5 knots are compared to 10-knot levels in Fig. 12. These noise levels represent 1-yard source levels. Noise levels for 500-yard ranges are given in Appendix D.

The most important contributor to Dawn Princess's 10-knot noise spectra was noise energy from the synchroconverters in combination with the propulsion motors. Noise from other equipment was present at lower levels. Unlike the other ships that were tested, cavitation noise was minimal to nonexistent at 10 knots. Noise levels for Dawn Princess were not measurable at frequencies above 5 kHz due to interference from wind and rain noise.

As shown in Fig. 12, the maximum noise levels at 5 and 10 knots were comparable, however noise levels for several frequency bands were actually higher at 5 knots. Noise in these bands was due to synchroconverter/propulsion motor noise. At frequencies above 1 kHz, noise levels were slightly higher than at 10 knots for reasons that were not determined.

Additional discussion of Dawn Princess's noise signatures may be found in NSWC DET's original reports to Princess Cruise Lines, refs. (7) and (8), and in British Aerospace's report to Princess Cruise Lines, ref. (9).

Norwegian Wind

The Norwegian Wind was powered by a pair of "father-son" diesel propulsion engines. Each father-son complex consisted of an 8-cylinder and a 6-cylinder diesel engine coupled to a propulsion shaft through a reduction gear. Norwegian Wind was the only ship tested that was equipped with this type of propulsion system. Electrical power on the ship was generated by a separate system using two 8-cylinder diesel generators.

Norwegian Wind's 10-knot underwater noise levels are shown in Fig. 13. The most significant noise peaks are labeled by source. Noise levels for 19 knots are compared to 10-knot levels in Fig. 14. These noise levels represent 1-yard source levels. Noise levels for 500-yard ranges are given in Appendix D.

The most important contributor to Norwegian Wind's 10-knot noise spectrum was noise energy from the propulsion system, especially the propulsion diesels. Cavitation noise was important at frequencies above 200 Hz. Reduction gear noise controlled levels in the 315 and 630 Hz frequency bands. Noise from other equipment was present at lower levels.

As shown in Fig. 14, 19-knot noise levels were up to 30 dB higher in isolated bands compared to 10-knot levels. The source of the high level peak at 63 Hz was not identified, but it was probably propulsion related. At frequencies above 200 Hz, 19-knot noise levels were higher due to increased cavitation.

Additional discussion of Norwegian Wind's noise signatures may be found in NSWC DET's original Norwegian Wind reports to Norwegian Cruise Lines, refs. (10) and (11).

Norwegian Sky

A diesel-electric propulsion system powered the Norwegian Sky. Six diesel generators provided all electrical service to the ship, including power to the main propulsion motors. The ship was equipped with a synchroconverter to convert constant frequency AC electrical power from the generators to variable frequency AC power to drive the electric propulsion motors.

Norwegian Sky's 10-knot underwater noise levels are shown in Fig. 15 in one-third octave format with the most significant noise peaks labeled by source. Noise levels for 14 knots are compared to 10-knot levels in Fig. 16. These noise levels represent 1-yard source levels. Noise levels for 500-yard ranges are given in Appendix D.

Norwegian Sky's noise spectra were dominated by noise energy from the electric propulsion system and broadband cavitation noise. At 10 knots, components from the synchroconverters in combination with the electric propulsion motors were prominent at frequencies below 200 Hz, and propeller cavitation was the dominant source of noise energy at frequencies above 200 Hz. Contributions from the diesel generators and a generator housing resonance were also present.

As shown in Fig. 16, 14-knot noise levels were slightly higher than 10-knot levels at frequencies above 400 Hz due primarily to cavitation. From 80 to 315 Hz, noise levels were up to 6 dB lower at 14 knots, probably due to speed dependent propulsion noise.

Additional discussion of Norwegian Sky's noise signatures may be found in NSWC DET's original Norwegian Sky report to Norwegian Cruise Lines, ref. (12).

10-Knot Summary

The 10-knot one-third octave noise spectra for each of the six ships are compared in Fig. 17. This comparison shows significant disparity in noise levels and frequency character at frequencies below about 1 kHz due to differences in propulsion related noise between vessels. Above 1 kHz, cavitation noise levels also varied among ships, but they all (perhaps with the exception of the Dawn Princess) demonstrated broadband frequency character that is typical of cavitation noise. The variation in cavitation noise levels between ships was likely due to differences in propeller design and, for ships with controllable pitch propellers, the pitch/rpm combinations that were used at the 10-knot test speed.

No single ship was clearly the quietest or noisiest over the entire frequency range when compared to the entire group. However, a few ships were distinctive in isolated frequency regions. Above 1 kHz the Dawn Princess was significantly lower than the other ships in terms of cavitation noise, but its noise levels were the highest in the neighborhood of 100 Hz due to propulsion related noise. Also, above 1 kHz, Norwegian Wind's cavitation noise levels were higher than the other vessels, but at lower frequencies its noise levels were well within the minimum and maximum levels exhibited by the other ships. In contrast, Crystal Harmony's noise levels from 12 to 40 Hz were the highest of all levels due to propulsion related energy while its cavitation noise levels above 1 kHz were neither the highest nor the lowest.

The comparison in Fig. 17 also shows that no propulsion system type was clearly quieter than the others were. However, primarily because of frequency converter and electric propulsion motor noise energy, noise levels from the diesel-electric ships generally reached higher levels at frequencies below 1 kHz compared to the steam powered Universe Explorer and the direct-diesel Norwegian Wind. It is important to recognize that, while this result is true for the 1-yard levels given in Fig. 17, conclusions regarding low frequency propulsion noise will not necessarily hold at greater distances from the ship where low frequency noise will be de-emphasized due to acoustic propagation effects. These effects will be demonstrated further later in this report.

Figure 17 also shows no distinct advantage to controllable pitch propellers. The two ships with constant pitch propellers, Universe Explorer and Dawn Princess, exhibited lower cavitation noise levels at 10 knots compared to their controllable pitch counterparts. It is possible that the ships with controllable pitch propellers did not operate in their optimum (optimum with respect to cavitation) rpm/pitch combinations at 10 knots. It is also possible that the ship operators had not established rpm/pitch combinations that minimized cavitation for their respective vessels over their normal operational speed range. So, the cavitation noise levels from these ships could potentially be reduced if optimum pitch/rpm conditions were known. Dawn Princess was distinguished from the other ships in that it was the only ship with a six-bladed propeller – all other ships had four-bladed propellers. It is not clear at this point if this design difference was solely responsible for Dawn Princess's lower cavitation noise levels, but it is true that propellers can be designed with varying degrees of attention given toward minimizing cavitation.

For noise comparison purposes it is sometimes less complex to compare noise levels from different sources using their overall *sound levels* rather than using the spectral representation. This approach simplifies comparing noise levels, but sacrifices some of the information contained in the spectrum. Sound level is a measure of all of the acoustic energy represented by a given spectrum. It is derived by summing the noise energy contained in all of the one-third octave bands to arrive at a single number representing the total acoustic energy that was measured[*].

The overall sound levels for each cruise ship are compared in Fig. 18. The sound levels in Fig. 18 were derived using the 10-knot, 1-yard one-third octave spectra shown in Figs. 5 through 16. This comparison shows that 10-knot levels ranged from 175 to 185 dB[**]. The highest level was attributed to Crystal Harmony and was due primarily to electric propulsion system energy at 16 Hz. Statendam's sound level was controlled by diesel generator noise at 10 Hz. Norwegian

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[*] Note that overall sound levels are determined more by the maximum one-third octave band levels for each ship and the lower one-third octave band levels for a given ship have essentially no influence on the overall sound level. This result occurs because, when adding energy represented by decibels, smaller decibel values contribute very little to the overall sum. A difference of 10 dB corresponds to a 10 fold difference in energy level. A 20 dB difference corresponds to a 100 fold difference in energy level.

[**] To put this 10 dB range into perspective, humans can distinguish sound pressure differences of about 3 dB and a 10 dB increase is perceived as a doubling in sound intensity. The difference between the peak noise of a single vehicle passing by and heavy traffic is about 10 dB.

Sky's overall sound level was heavily influenced by propulsion related noise at 63 and 125 Hz and diesel generator noise at 31 Hz. A propulsion noise peak at 100 Hz was the primary contributor to Dawn Princess's 10-knot sound level. Propulsion diesel noise was the main contributor to Norwegian Wind's overall sound level. The primary source of noise for Universe Explorer's overall sound level was related to the ship's turbine generator. Note that the results shown in Fig. 18 will be different at speeds other than 10 knots and at ranges other than 1 yard. Effects of ship speed and distance between ship and noise measurement point will be discussed below.

Speed Dependence

In general, ship noise signatures vary with speed and the cruise ships that were tested were no exception. As ship speed increases, noise levels typically increase and the frequency character of the noise spectrum usually changes. Some components of a ship's noise signature, particularly propulsion related noise, are inherently dependent on ship speed. Other signature components may be independent of ship speed. The cruise ship signatures presented in this report contain both speed dependent and speed independent features.

Examples of speed dependent, propulsion related noise that were observed are listed below by propulsion type.

(a) Diesel-electric: frequency converter/electric propulsion motor noise.
(b) Diesel-direct: propulsion diesel engines, reduction gears.
(c) Steam turbine: main propulsion turbine, reduction gears.

The frequency at which these signature components occurred changed with ship's speed since they were directly dependent on propulsion shaft rpm. Usually the noise levels associated with these sources also increased with increasing speed, however in some cases noise levels actually decreased with nominal increases in speed, due to resonance effects and other factors.

In addition to the sources listed above, ship propeller and/or hull-related cavitation noise was also speed dependent. As ship speed increased, cavitation noise increased both in level and in the breadth of the range of frequencies over which it occurred.

Examples of speed dependent noise in the cruise ship signatures included:

(a) Increases in cavitation noise between 10 and 15 knots in Crystal Harmony's signatures in Fig. 6.

(b) Shift in propulsion related energy from 16 to 25 Hz between 10 and 15 knots in Crystal Harmony's signatures in Fig. 6.

(c) Increases in cavitation noise between 10 and 18 knots in Statendam's signatures in Fig. 8.

(d) Decreases in the broadband noise levels at 160 Hz between 10 and 18 knots in Statendam's signatures in Fig. 8.

(e) Shift in propulsion related energy from 50 to 100 Hz and 400 to 630 Hz between 10 and 15 knots in Universe Explorer's signatures in Fig. 10.

(f) Increases in cavitation noise between 10 and 15 knots in Universe Explorer's signatures in Fig. 10.

(g) Shift in propulsion related energy from 50 to 100 Hz and diminishing of peaks at 315 and 800 Hz between 5 and 10 knots in Dawn Princess's signatures in Fig. 12.

(h) Increases in cavitation noise above 200 Hz and noise from 63 Hz peak between 10 and 19 knots in Norwegian Wind's signatures in Fig. 14.

(i) Increase in propulsion noise at 63 Hz, reduction in 125 to 315 Hz propulsion noise, and an increase in propulsion related broadband noise above 400 Hz between 10 and 14 knots in Norwegian Sky's signatures in Fig. 16.

As another measure of noise level dependence on speed, the 1-yard overall sound levels for each ship at its alternate test speed (i.e. non 10-knot speed) were established and plotted alongside their respective 10-knot levels in Fig. 19. This comparison shows that overall sound levels from three diesel-electric ships - Crystal Harmony, Dawn Princess, and Norwegian Sky - showed essentially no speed dependence at the two speeds tested. Statendam and Universe Explorer exhibited less than 10 dB increase in level at the higher speed. Norwegian Wind, the direct-diesel ship, showed the greatest speed dependence due to an almost 20 dB increase in propulsion noise at 19 knots.

Not only did three ships show little speed dependence for the two speeds that were tested, but also Crystal Harmony's sound level was actually slightly lower at the higher speed. This reduction in total noise energy was due to lower electrical propulsion system noise. For these three ships, at least in terms of 1-yard sound levels, it would be difficult to perceive any difference in overall noise energy between the two speeds that were tested.

Given the fact that ship signatures were speed dependent, and that the dominant noise contributors were usually propulsion related, it is likely that optimum operating speeds to minimize a ship's radiated noise levels could be identified. Such an approach might involve establishing the best speed within a certain speed range, or identifying the best propeller rpm and propeller pitch combination to achieve a given speed while minimizing propeller cavitation.

Some cruise ship noise signature components were not speed dependent. Sources such as constant rpm diesel generators, turbine generators, air conditioning plants, and pumps did not increase in level or exhibit change in frequency character with changes in ship's speed. Examples of cruise ship signature components that were not speed dependent include:

(a) Diesel generator noise at 10 Hz in Statendam's 10 and 18 knot signatures in Fig. 8.
(b) Turbine generator noise at 20 Hz in Universe Explorer's 10 and 15 knot signatures in Fig. 10.
(c) Diesel generator noise at 31 Hz in Norwegian Sky's 10 and 14 knot signatures in Fig. 16.

Range Dependence

As mentioned previously in this report, the distance, or range, from the cruise ship noise source to the observer exposed to the noise is an important variable. Two factors are important: (a) noise levels are reduced due to spherical or cylindrical spreading of the acoustic wavefront as it propagates, and (b) multipath propagation effects that influence low frequency noise levels significantly*.

Spherical or cylindrical spreading effects reduce noise levels across the entire frequency range according to 20xlog(range) or 10xlog(range), respectively, depending on water depth, propagation range, bottom type, etc. in a given undersea area. It is also possible to have some combination of these two spreading types occurring. More information on empirically

* At long ranges and high frequencies, losses due to absorption can also become significant.

determined spreading types prevalent in certain areas of Glacier Bay may be found in ref. (13). Table 3 lists some sample spreading loss numbers that represent the amount of spreading loss that would be expected in going from 1 yard to longer ranges. A useful rule-of-thumb for spherical spreading is that, for every doubling of the range, the noise level is reduced 6 dB.

Table 3 - Spreading Loss at Various Ranges

Range (yd)	Spherical Spreading (dB)	Cylindrical Spreading (dB)
1	0	0
10	20	10
100	40	20
500	54	27
1000	60	30
2000	66	33

As mentioned above, multipath propagation effects are also important when translating 1-yard source levels to levels at other ranges. This consideration is particularly important for noise sources located close to the surface of the water, i.e. cruise ships and watercraft. The overall effect is that low frequency noise levels are de-emphasized at longer ranges. These multipath effects must be considered in addition to spreading loss. This report will not delve into this subject in detail, but several illustrative examples will be given.

Figure 20 shows a comparison of Crystal Harmony's 1-yard and 500-yard noise spectra that illustrates the combined effect of spherical spreading and multipath effects. Above 250 Hz the only difference between the two spectra is due to spherical spreading, however the de-emphasis of noise levels at lower frequencies in the 500-yard spectrum is notable. In the 1-yard signature the energy at 16 Hz is the dominant source of acoustic energy. At 500 yards the energy at 400 Hz becomes equally important. This comparison illustrates the importance of taking range considerations into account when assessing noise signatures. For further comparison, the 500-yard noise spectra for each cruise ship are given in Appendix D.

Figure 21 shows the effect of range on the 1-yard overall sound levels for each cruise ship at 10 knots. The dominant effect is the general reduction in noise level due to spherical spreading: 40 dB from 1 to 100 yards, and 14 dB from 100 to 500 yards. However, the effect of low frequency de-emphasis is also apparent, particularly with regard to its effect on the rankings of each ship at the various ranges. For example, at 1 yard, Crystal Harmony exhibited the highest sound level, but at 500 yards it was ranked lower than three other ships because its low frequency levels, which were important at 1 yard, were de-emphasized at 500 yards. In terms of controlling overall sound level, this result illustrates that mid-frequency energy will typically be more important than low frequency noise at practical ranges such as ¼ mile.

Another notable result apparent in Fig. 21 is that Universe Explorer's 10-knot overall sound level was lower than the others at all of the ranges considered. Universe Explorer was the only steam powered ship that was tested, and it was also the lowest horsepower and smallest by a significant margin – 1/3 to ½ the displacement of the other ships. Both of these factors likely worked toward Universe Explorer's acoustic advantage at 10 knots.

The effect of range on both the 10-knot and alternate speed sound levels is shown in Fig. 22. This graph demonstrates that the relative speed independence of some ships' overall sound levels could be diminished at longer ranges. Specifically, for 1-yard levels, Crystal Harmony's sound level showed little change when increasing speed from 10 to 15 knots, however its 500-yard sound levels increased 6 dB, showing greater speed dependence. This result occurred because, in this case, low frequency signature components controlled the 1-yard sound levels and more speed dependent mid-frequency energy governed the 500-yard sound levels. For the case of the Norwegian Sky and Dawn Princess, Fig. 22 shows that the their speed independence was maintained over the 1, 100, and 500 yard ranges.

Range of Noise Levels

Since a total of six cruise ships with three distinctly different propulsion systems were evaluated, the data set included in this report provided an opportunity to establish a range of levels that might be representative of the types of large cruise ships that sail Southeast Alaska waters. Figure 23 shows an envelope representing the range of 1-yard levels that were measured at 10 knots. In a given one-third octave frequency band the difference between minimum and maximum levels ranged from 6 to 23 dB. An envelope representing the range of levels that were measured at the higher speeds, 14 to 19 knots, is shown in Fig. 24 (Dawn Princess 5 knot levels are not included in this graph). Given the speed range involved, the range of levels across this envelope was greater. In this case, the difference between minimum and maximum levels ranged from 5 to 26 dB.

The range of overall sound levels is shown in Fig. 25 at selected ranges for the 10-knot data set and the alternate speed data set. The maximum 10-knot sound levels at 1, 100, and 500 yards were 185, 137, and 120 dB, respectively. A useful result from Fig. 25 is that, at each range, maximum levels show an acoustic benefit in running at 10 knots versus the higher speed. At 1, 100, and 500 yards, the highest 10-knot levels were 10 to 16 dB lower than the highest levels at high speed. In certain cases, however, there may be exceptions - Norwegian Sky for example, as shown in Fig. 22.

Cruise Ship Noise Compared to Other Underwater Noise Sources

Cruise ships were compared to other sources of underwater noise as a means of ranking the intensity of their noise energy relative to other sources, both loud and quiet. In this section cruise ship noise levels are compared to naturally occurring ambient noise and to noise from other marine vessels.

Figure 26 compares the 10-knot max/min cruise ship noise envelope for both 1 yard and 500 yard ranges with widely used wind generated ambient noise levels from ref. (1). These ambient noise curves represent the typical, naturally occurring, wind generated, underwater ambient noise levels that are encountered in open water environments at different wind speeds. Figure 26 shows that noise levels from cruise ships at 10 knots at a distance of both 1 yard and 500 yards would typically be expected to exceed the naturally occurring wind related noise in a given area.

It is possible to take the data in Fig. 26 and estimate the range at which ship noise would be masked by local wind noise. As an illustration using the data in Fig. 26, at a range of about 4 miles, 11 to 16 knot wind noise would rival the cavitation noise occurring in the 1 to 40 kHz region of the cruise ship signatures. That is, the cavitation noise from a typical cruise ship would begin to be masked by local 11 to 16 knot wind noise when the ship is about 4 miles distant. Other lower frequency ship noise would probably still be discernable.

For comparative purposes, 10-knot cruise ship noise levels were also plotted versus published noise levels for other marine vessels. Figure 27 shows the 10-knot cruise ship max/min envelope versus a generic, slow speed, submerged submarine, ref. (14); a 15 foot Zodiac boat, ref. (15); a 24 foot outdrive boat, ref. (15); a 380 ft diesel powered oceangoing ship; and a generic, large surface vessel at high speed, ref. (14)*. The 10-knot cruise ships levels were comparable to the 24 foot outdrive and 380 foot diesel noise levels. Cruise ship noise levels were generally higher than the 15 foot Zodiac boat levels, with the exception of levels in the 3 to 6 kHz frequency region, where Zodiac outboard noise levels were comparable to, or higher than, cruise ship levels. It is not surprising that Zodiac outboard noise is significantly lower in level than cruise ship noise at lower frequencies, yet higher in level at higher frequencies. This result is due to the size of the vessels and their propulsion system mechanical characteristics – primarily the high power, low rpm propulsion of the cruise ship versus the high rpm outboard engine and propeller. The 10-knot cruise ship noise levels were lower across the spectrum compared to the high-speed large surface vessel levels. In addition, relative to the low-speed submarine noise levels, cruise ship noise levels were consistently higher.

These results demonstrate that the cruise ships included in this project were neither the noisiest nor the quietest vessels known to operate at sea. In addition, in some frequency bands their levels may be exceeded by smaller craft, even those using relatively small outboard motors. Also, as a reminder, note that the levels compared in Fig. 27 are 1-yard levels, i.e. the levels that would be *measured* at 1 yard from the vessel if it were possible to do so. At greater distances, all

* The noise spectra shown in Fig. 27 were derived from spectra given in the reference documents. The spectra in the reference documents were 1-meter levels and the ref. (14) levels were reported in spectrum level (1 Hz bandwidth). This information is noted here so that the reader understands that the levels were converted to the representation used in this report (i.e. one-third octave level). There may be some loss in accuracy when converting spectrum levels to one-third octave levels (and vice versa) when the narrowband character of a noise signature is not known and accounted for.

of the noise levels in Fig. 27 will be reduced, and the shapes of the noise spectra will also change.

To rank noise levels relative to each other, the overall sound levels of the cruise ships were plotted in scale form along with the levels associated with other marine vessels and ambient noise in Fig. 28. Figure 28 shows ship noise levels at 1 yard and ¼ nautical mile (500 yards). Cruise ship levels are shown as a range of levels for both 10 knots and as a range for higher speeds (14 through 19 knots). Overall sound levels for the generic high speed ship, 15 foot Zodiac boat, generic slow speed submarine, and wind generated ambient noise for Glacier Bay on quiet and windy days are also given.

Figure 28 shows that cruise ship levels occupy the mid region of the scale. They are above Zodiac boat and submarine levels, and above the entire range of naturally occurring wind related ambient noise levels on both the 1-yard and ¼ nautical mile scale. The highest level cruise ship at high speed is 5 dB below the generic large ship at high speed.

SUMMARY AND CONCLUSIONS

Underwater noise levels for six Southeast Alaska cruise ships ranging in size from 23 to 77 thousand gross tons and from 617 to 856 feet in length were established experimentally at SEAFAC in September 2000 and June 2001. At 10 knots overall sound levels for all ships ranged from 175 to 185 dB relative to 1 microPascal at 1 yard and the highest one-third octave band level was 182 dB. At higher speeds, 14 to 19 knots, overall sound levels ranged from 178 to 195 dB. Diesel-electric, direct-diesel, and steam turbine propulsion plants were represented among the ships tested.

Cruise ship noise character was typically governed by propulsion system type. Noise energy from electric propulsion motors in combination with frequency converters and diesel generators was dominant in the signatures of the diesel-electric ships. Propulsion diesel and reduction gear noise were important contributors to the underwater noise of the direct-diesel ship that was tested. For the steam plant equipped ship, turbine generator, propulsion turbine, and reduction gear noise were the most significant noise items in the ship's signature.

At low and mid frequencies, differences between the cruise ship noise signatures were generally due to differences in propulsion plant type. At higher frequencies, noise signatures were distinguished by differences in cavitation noise levels.

Cruise ship noise levels were measured at a nominal distance of 500 yards. These noise levels were projected to ranges of 1 yard and 100 yards. At 10 knots, the diesel-electric ships exhibited the highest overall 1-yard and 100-yard sound levels. Because of noise propagation effects, at ¼ mile the 10-knot diesel-electric sound levels were comparable to the direct-diesel levels. At 10 knots, steam powered cruise ship* sound levels were the lowest of the six ships that were tested. Propulsion plant related noise sources were the primary contributors to these overall sound levels - they accounted for the majority of the differences between the overall sound levels from each ship. At practical ranges such as ¼ mile or more, mid-frequency propulsion plant related energy may become more important than low frequency noise (less than 100 Hz) due to the de-emphasis of low frequency energy that occurs at longer ranges.

Cruise ship cavitation noise levels were variable among ships. At 10 knots, the difference between the highest and lowest cavitation noise levels was as much as 16 dB. No distinct advantage was attributable to ships with controllable pitch propellers, because the two ships that exhibited the lowest level cavitation at 10 knots were the two ships with fixed pitch propellers. It should be noted, however, that the ships with controllable pitch propellers may not have operated in their best rpm/pitch combination with regard to minimizing cavitation. Further testing would be required to determine whether the cavitation performance of the controllable pitch propellers could be improved by operating at other pitch settings.

Although each ship was only tested at two speeds, some conclusions were drawn regarding speed dependence. Among the ships tested, some ships exhibited greater noise

* Note that the steam powered cruise ship was the also the oldest and smallest ship tested. Its displacement was 1/3 to ½ the displacement of the other ships.

dependence on speed than other ships. The noise from diesel-electric powered ships was generally less dependent on speed than the direct-diesel and steam powered ships. For the direct-diesel and steam powered ships (19 and 15 knots, respectively) noise levels were substantially higher at essentially all frequencies at the higher speeds, especially for the direct-diesel. For all ships but one (which was only tested at 5 and 10 knots) cavitation noise levels increased, usually significantly, at higher speeds.

For the diesel-electrics, propulsion noise in some frequency bands usually increased somewhat at higher speeds, but in certain cases actually decreased slightly at higher speeds. Yet, overall sound levels for these ships, which were primarily controlled by propulsion system related noise energy, were least affected by speed changes compared to the direct-diesel and steam powered ships. Of the four diesel-electric ships, Statendam exhibited more sound level dependence on speed, but it was tested at a higher alternate speed (18 knots) than the others of its type.

One ship had a unique speed dependent noise issue. At 10 knots it produced a distinct shaft related transient noise. This noise was not present at speeds even only slightly above or below 10 knots. Shipboard investigation localized the source of this noise to a correctable mechanical condition related to one of the propulsion shafts. This case illustrates that significant unusual, but sometimes relatively easily correctable, noise problems can occur at very specific speeds.

The results of this investigation indicate that 10-knot ship speed limits in Glacier Bay (versus 20 knots) would, in general, have a measurable effect on underwater cruise ship noise levels, although the results from the ships tested at 15 knots also indicate that there could be exceptions. Only two ships were tested at speeds near 20 knots, and their noise levels were higher at the higher speed, especially in the case of the direct-diesel ship. In general, anytime the horsepower generated by a ship increases, ship noise levels are expected to increase. Also, cavitation noise levels would be expected to be substantially greater at 20 knots compared to 10 knots.

With regard to exceptions to the above, two ships that were tested at speeds of about 15 knots, both diesel-electric, showed little change in overall sound level between 10 and 15 knots, although cavitation noise for one of these was substantially increased at 15 knots. Also, the overall sound levels for another diesel-electric were only slightly affected between 5 and 10 knots. As a result, in certain cases, a ship might be able to demonstrate small and acceptable increases in noise between, say, 10 and 15 knots. (The ships tested at 15 knots were not tested at 20 knots.)

Concerning ranking ships by propulsion type, at 10 knots the overall sound levels of the diesel-electrics were generally highest, followed closely by the direct-diesel and then the steam powered ship. Note however, that this ranking also roughly follows vessel size from largest to smallest, and that this ranking may not hold at speeds as high as 20 knots, because the diesel-electrics seemed to demonstrate less noise dependence on speed.

Based on the knowledge of cruise ship noise gained through this series of measurements, attempts to reduce cruise ship underwater noise levels should focus on propulsion plant related noise and cavitation noise. If relevant noise goals were developed that identified certain frequency ranges as more important than others, this focus could be further concentrated.

For propulsion noise, diesel-electric noise reduction should focus on improving frequency converter/electric propulsion motor related noise. Because this noise is inherent to the design of the plant, no low cost remedies exist. Future diesel-electric electrical systems would have to be designed to reduce these noise components. Also, the noise of the diesel generators themselves could be considered. The diesel generators on the ships covered in this report were isolation mounted to reduce vibration transmission to their hulls.

Likewise the direct-diesel plants are limited by their design. Diesel engine noise and reduction gear noise are not easily mitigated unless a significant mechanical deficiency exists.

Noise from the steam powered ship was also typical of ships of its type and vintage. Implementation of improvements in steam turbine and reduction gear design and configuration would probably be beneficial, but would certainly not be practical except in a new construction ship.

Some experimentation with ships that employ controllable pitch propellers might result in cavitation noise improvements for these ships. This approach would involve noise testing at various propeller pitch/rpm combinations to identify settings that minimize cavitation at specific speeds of interest. Also, especially for the diesel-electric and direct-diesel ships, such experimentation might help to identify pitch/rpm settings that result in nominal improvements in propulsion noise.

One objective of this project was to establish noise levels that might be typical of large cruise ships that are common in Southeast Alaska. Because four diesel-electric ships were evaluated, it is likely that typical noise levels for this type of ship are represented here. For the direct-diesel and steam powered ships, only one example of each was evaluated, however even the noise levels of these ships were not grossly different than the diesel-electrics when all were compared at 10 knots. It is also likely that, unless significant mechanical deficiencies come into play, the noise levels and character for the ships that were tested should be representative of ships of their class.

Significant new information regarding cruise ship noise levels, speed dependence, and range dependence has been gained. Although some additional work is recommended in the following report section, the knowledge gained through this project will be useful in understanding noise factors such as ship speed, and in projecting the effect of cruise ship operations on underwater noise in specific areas of interest.

RECOMMENDATIONS

After considering the knowledge that has been gained through this study and recognizing that further work will help refine and advance understanding of cruise ship underwater noise and its influence on underwater environments, a number of recommendations are offered. Some of these items pertain to gathering additional information and some are focused on utilizing the existing knowledge base.

1) Establish the frequency ranges of greatest concern with regard to impact on marine environments.
2) Given the effect of range on acoustic propagation effects, define distances from marine vessels that are most relevant to marine life that might be affected by vessel noise.
3) Develop underwater noise exposure goals or noise limits so that ship noise levels can begin to be assessed.
4) Identify important marine areas where ship noise impacts are of concern. Establish zones where ship activity is expected and where important adjacent marine environments are located. Define types of activity for each zone and dependence of these activities on time of year.
5) Using the results of the cruise ship noise measurements and results from items 1 through 4 above, incorporate noise considerations into vessel management procedures.
6) Until such time as information in items 1 through 4 is established, consider using the information gained in this study alone to develop noise guidelines. These guidelines could be either general "rule-of-thumb" guidelines, or more ship specific guidelines. General guidelines would be of the type where all ships follow the same rules, e.g. all adhere to the same speed limit. Ship specific guidelines would allow for ships to travel at higher speeds, if they demonstrate that their noise signatures are not significantly different at the higher speed.
7) Conduct noise measurements on new cruise ship types as they emerge. Noise levels for the new gas turbine powered ships should be measured.
8) As noise level comparisons in this report have shown, smaller marine vessels can produce noise levels rivaling the bigger ships in some frequency bands. Conduct noise measurements on other vessels common to marine environments of concern.
9) When conducting noise measurements on marine vessels, tests should be conducted at speeds that are relevant to marine areas of concern. Vessels should be tested at the same speeds so that meaningful comparisons can be performed.
10) Consider measuring noise from thrusters or other systems that ships might commonly operate.
11) Conduct cruise ship noise measurements using the hydrophone currently located in Glacier Bay at long distances and compare these results with the noise levels measured at SEAFAC. Use these comparisons to check noise propagation models that might be applied in Glacier Bay.
12) Conduct noise measurements to quantify cruise ship noise directivity. These measurements could be performed at SEAFAC or at Glacier Bay.
13) Consider testing ships in various equipment setups to minimize noise. For example, ships with controllable pitch propellers could be evaluated at various propeller rpm/pitch

combinations to establish settings that minimize cavitation and reduce propulsion plant noise.

14) If ship noise guidelines are established, develop means of checking ship acoustic health. Examples include:
    a. Establish acceptable noise levels for each ship class and check individual ship noise levels against this standard.
    b. Develop shipboard noise monitoring capabilities to detect and identify noise deficiencies using shipboard sensors that are periodically monitored. This capability could be used to monitor for unusual noise problems that might develop as a result of mechanical deficiencies.
    c. Monitor ship noise in Glacier Bay using sensor(s) located in Glacier Bay.

FIGURES

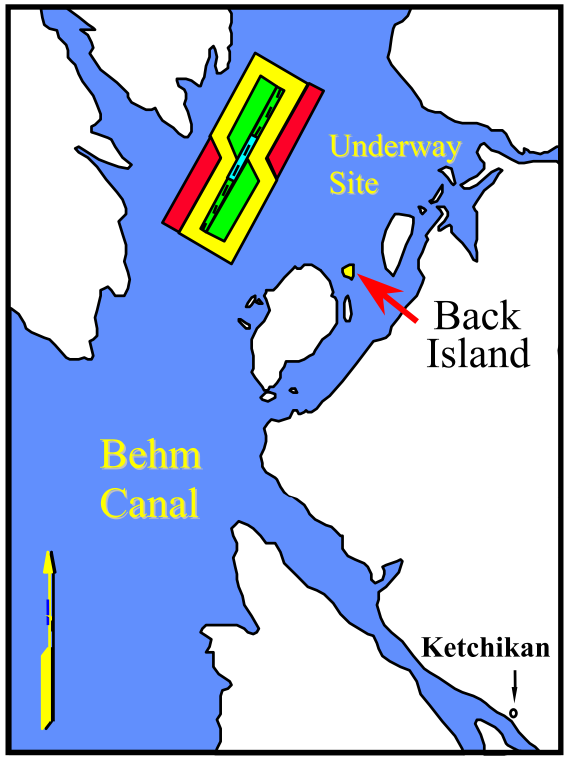


Fig. 1 Southeast Alaska Acoustic Measurement Facility

Crystal Harmony

Holland America Statendam

Universe Explorer

Dawn Princess

Norwegian Wind

Norwegian Sky

Fig. 2 Cruise Ships Tested at SEAFAC

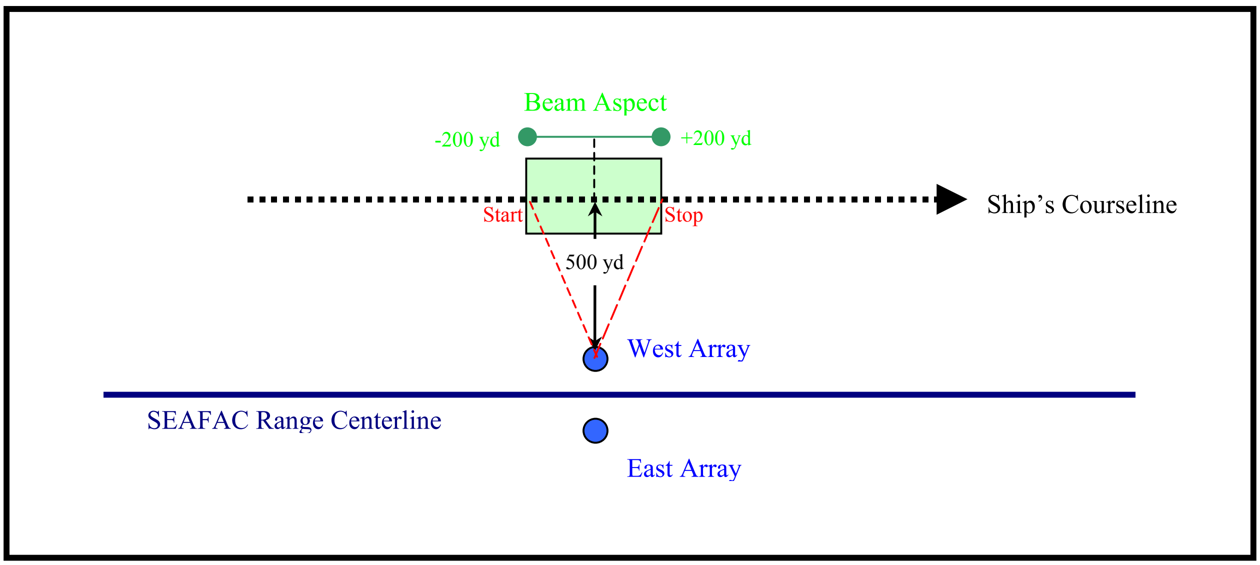
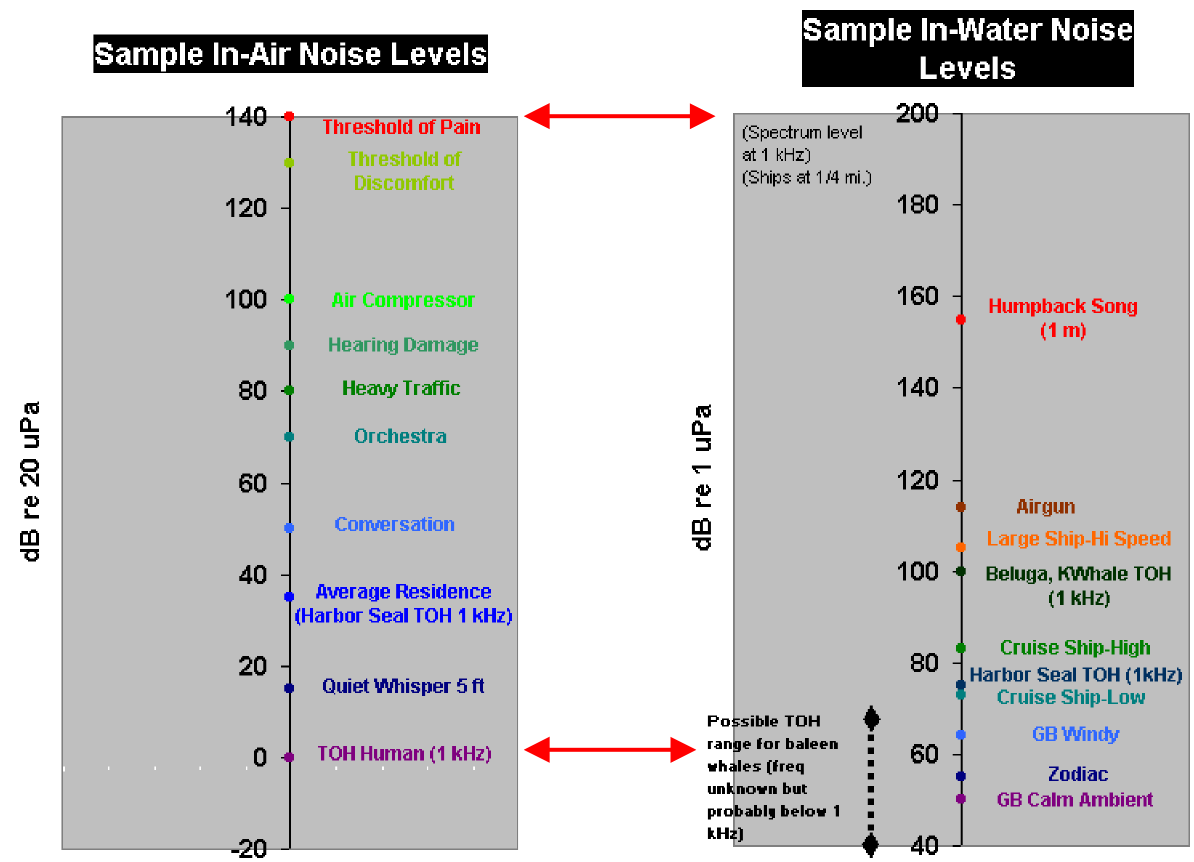


Fig. 3 Beam Aspect for Noise Measurement



(TOH = threshold of hearing)

Fig. 4 Sample In-Water and In-Air Noise Scales

(Threshold of hearing data for marine mammals from ref. 15)

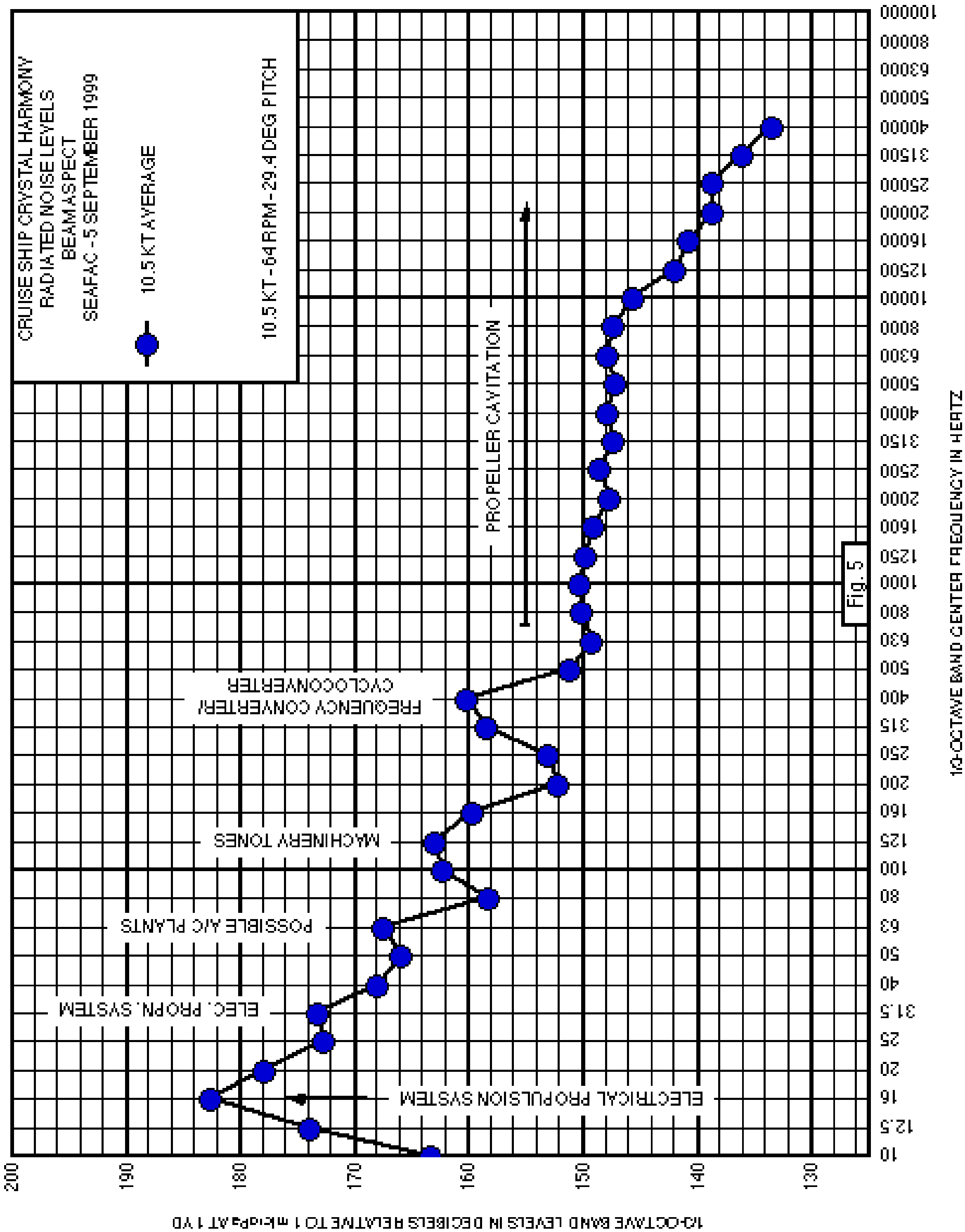


Fig. 5 Crystal Harmony – 10 knots

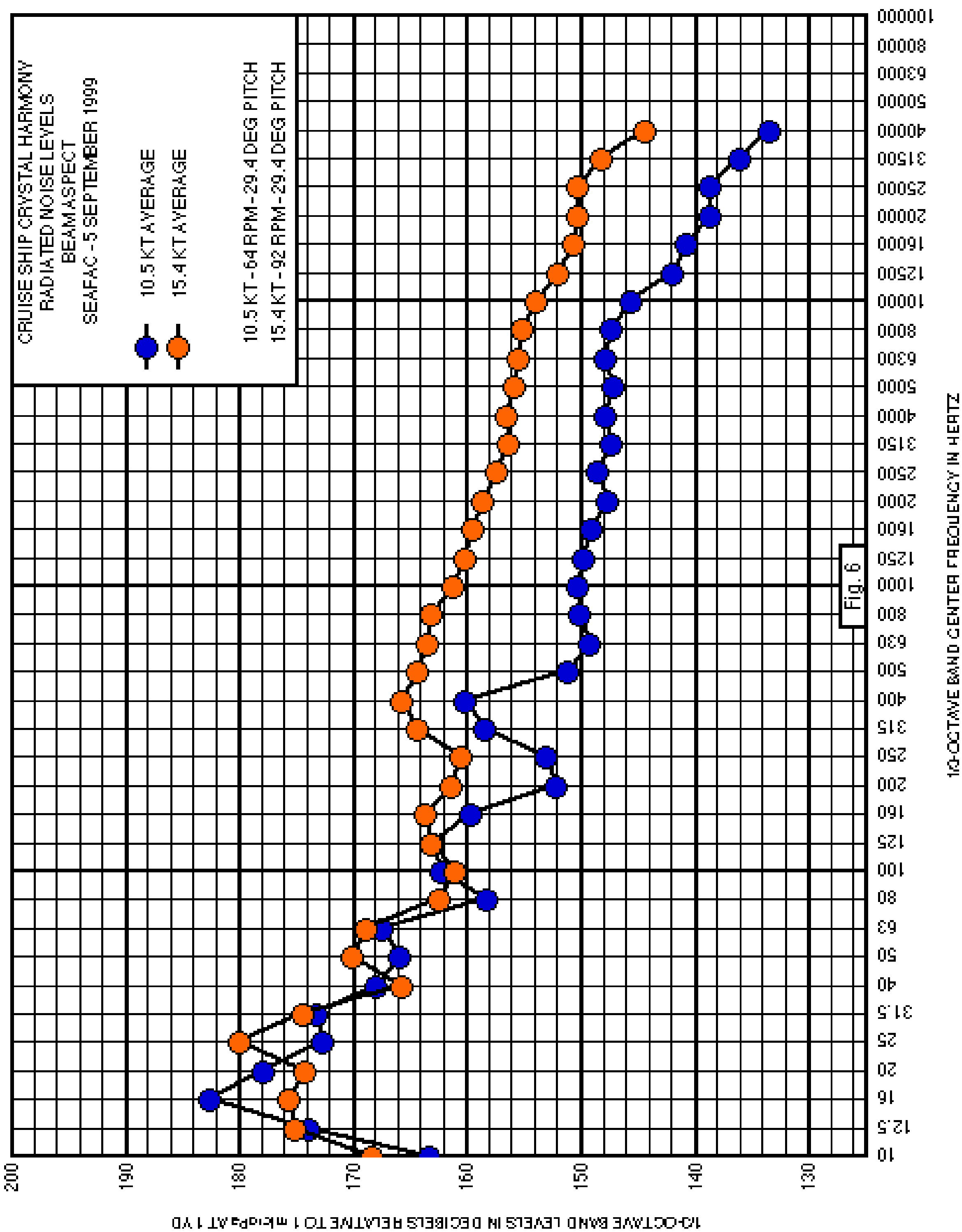


Fig. 6 Crystal Harmony – 15 knots

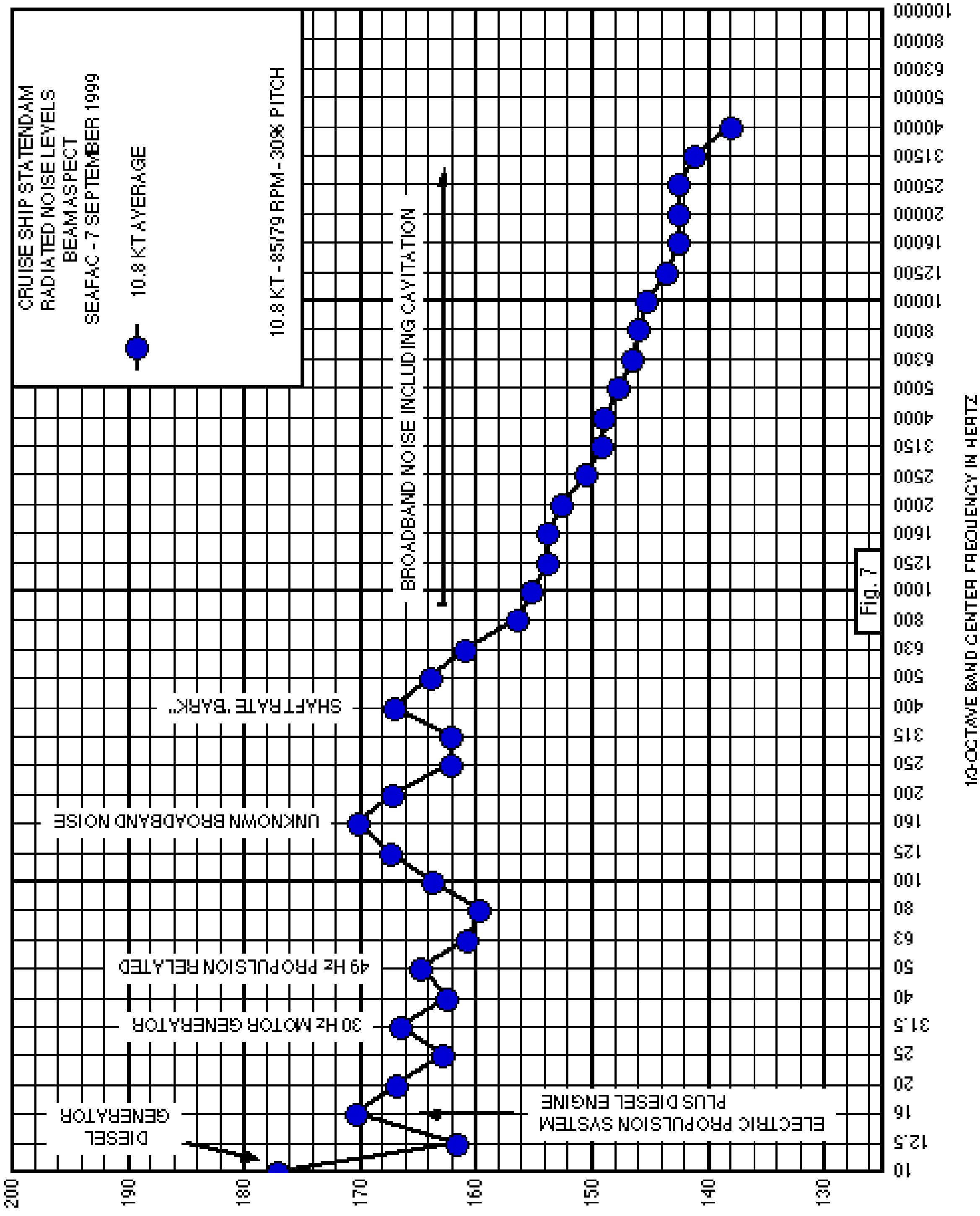


Fig. 7 Statendam – 10 knots

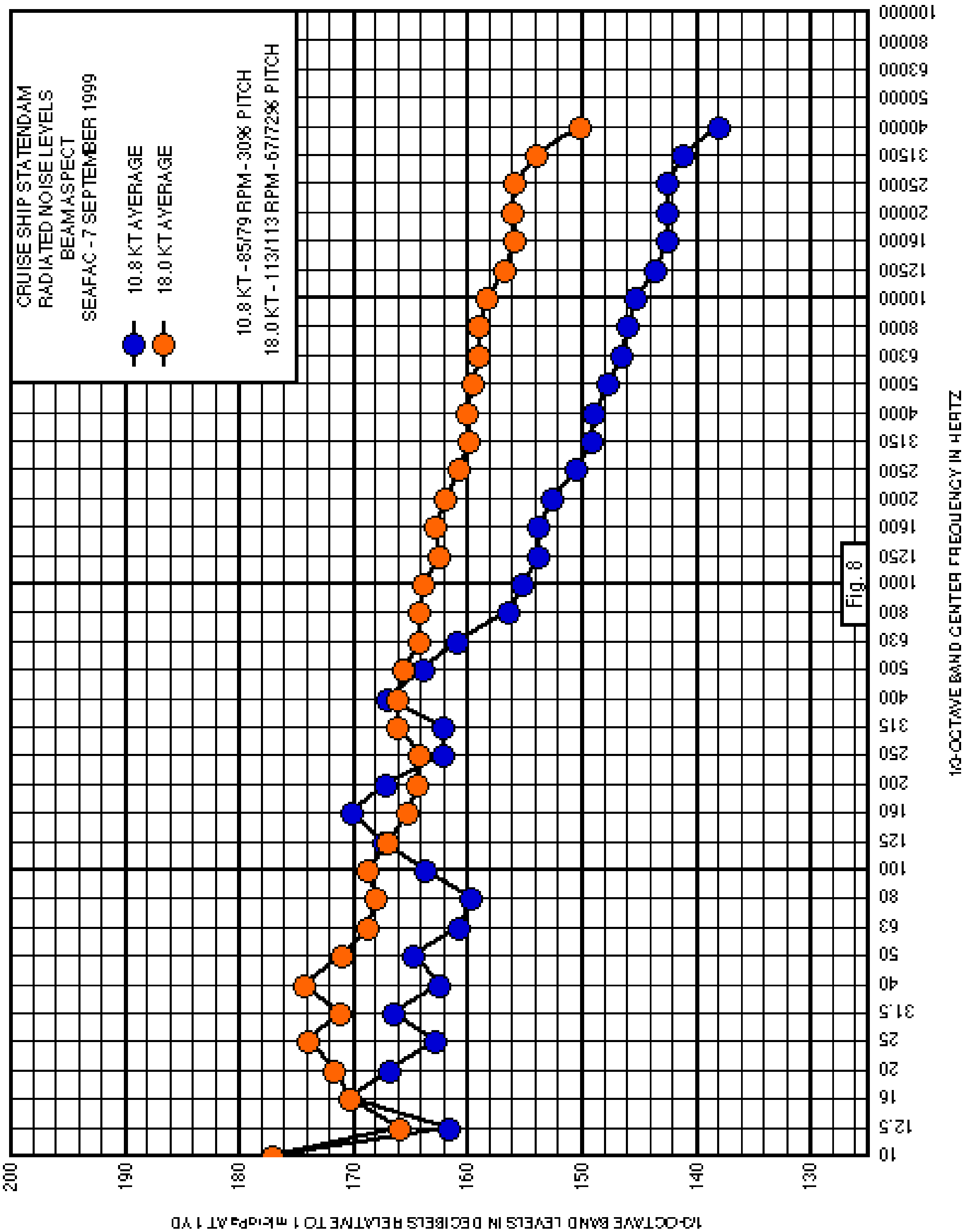


Fig. 8 Statendam – 18 knots

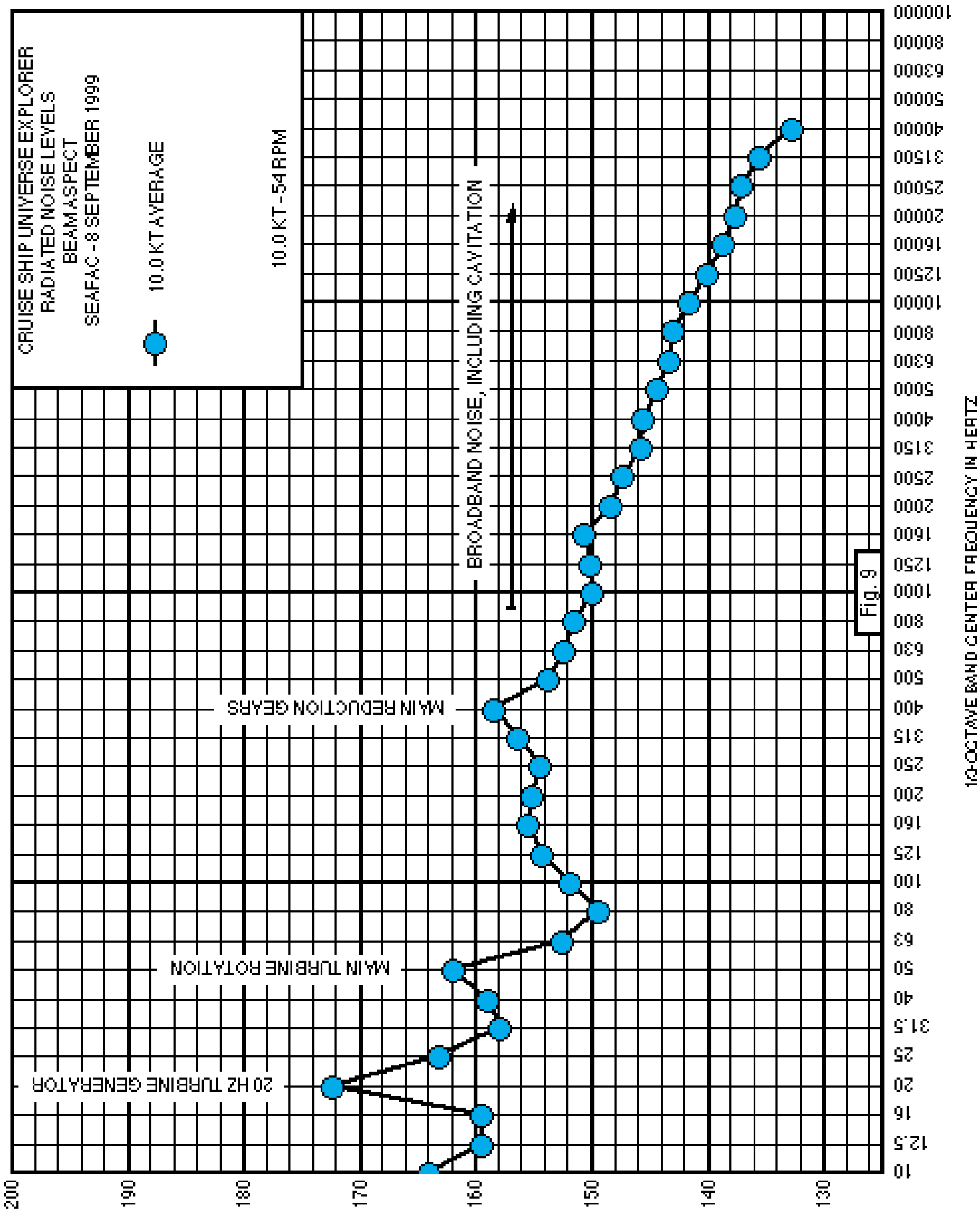


Fig. 9 Universe Explorer – 10 knots

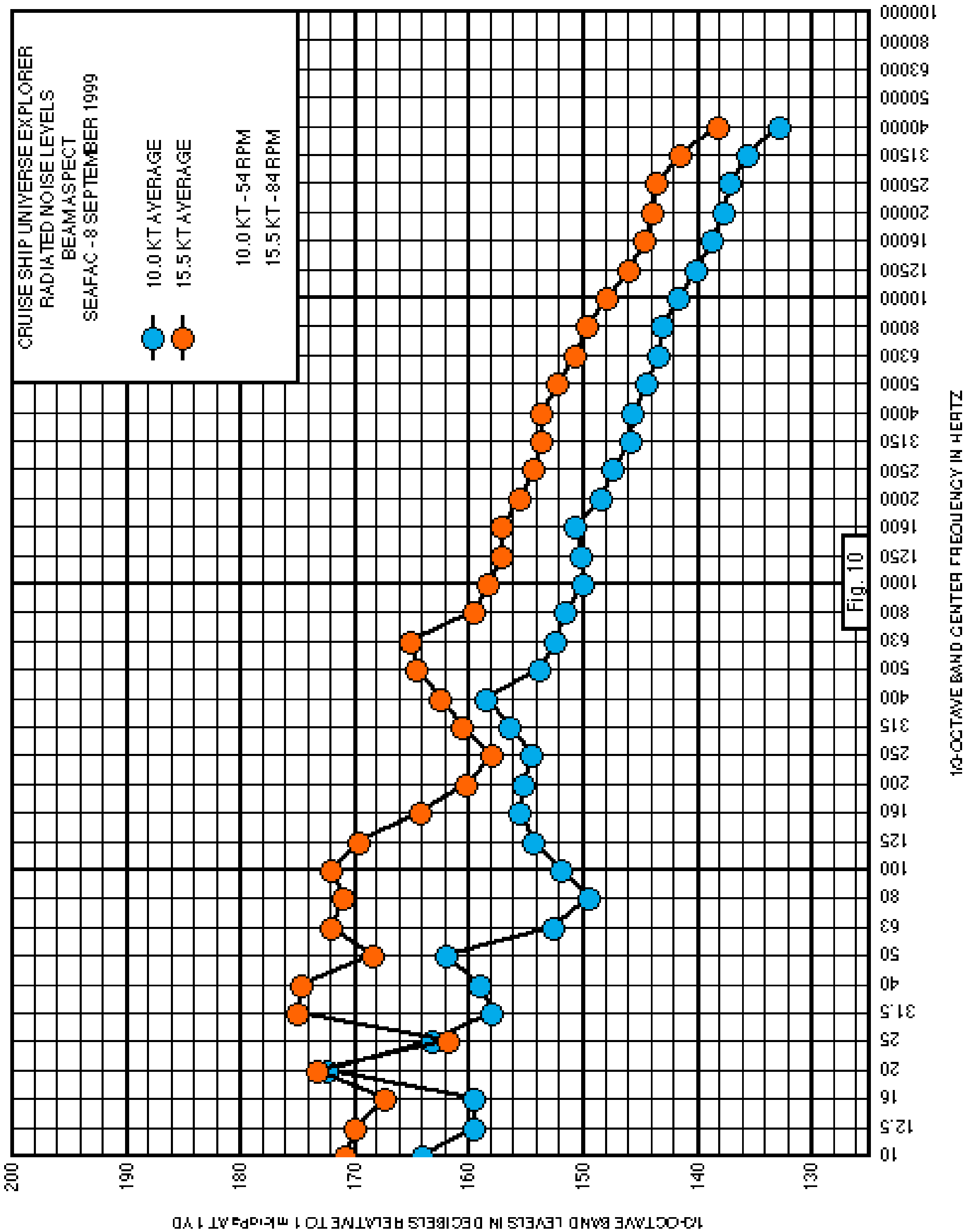


Fig. 10 Universe Explorer – 15 knots

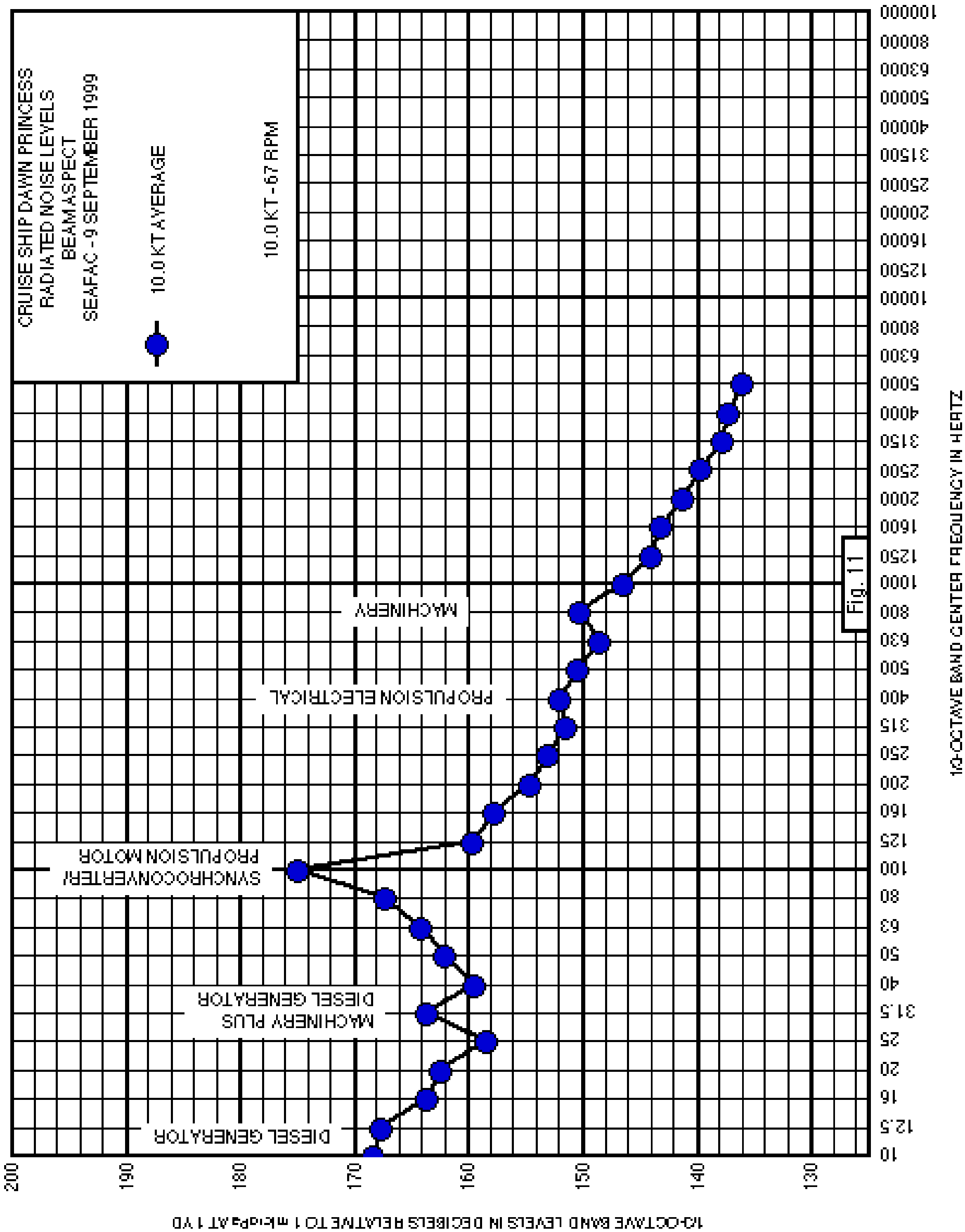


Fig. 11 Dawn Princess – 10 knots

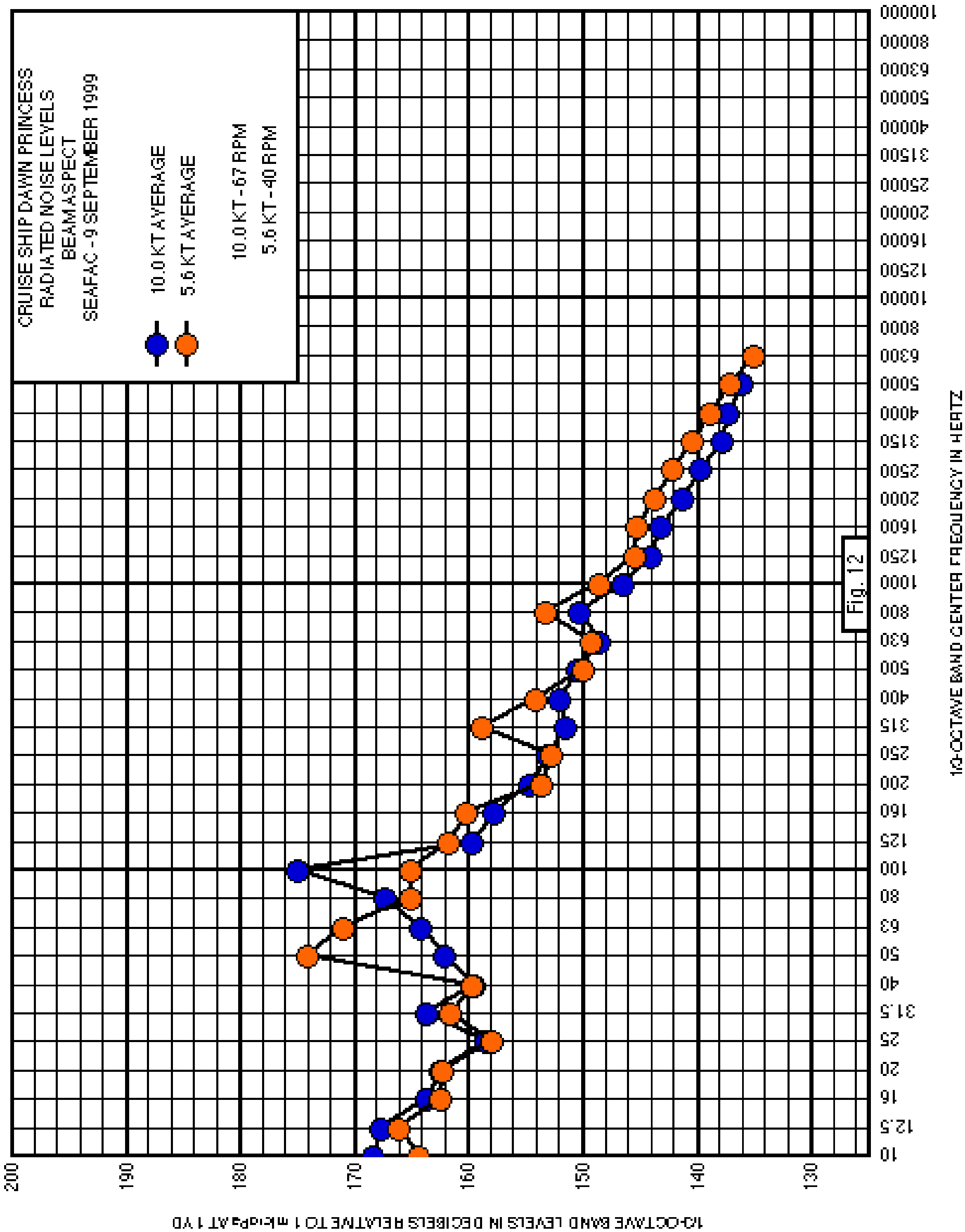


Fig. 12 Dawn Princess – 5 knots

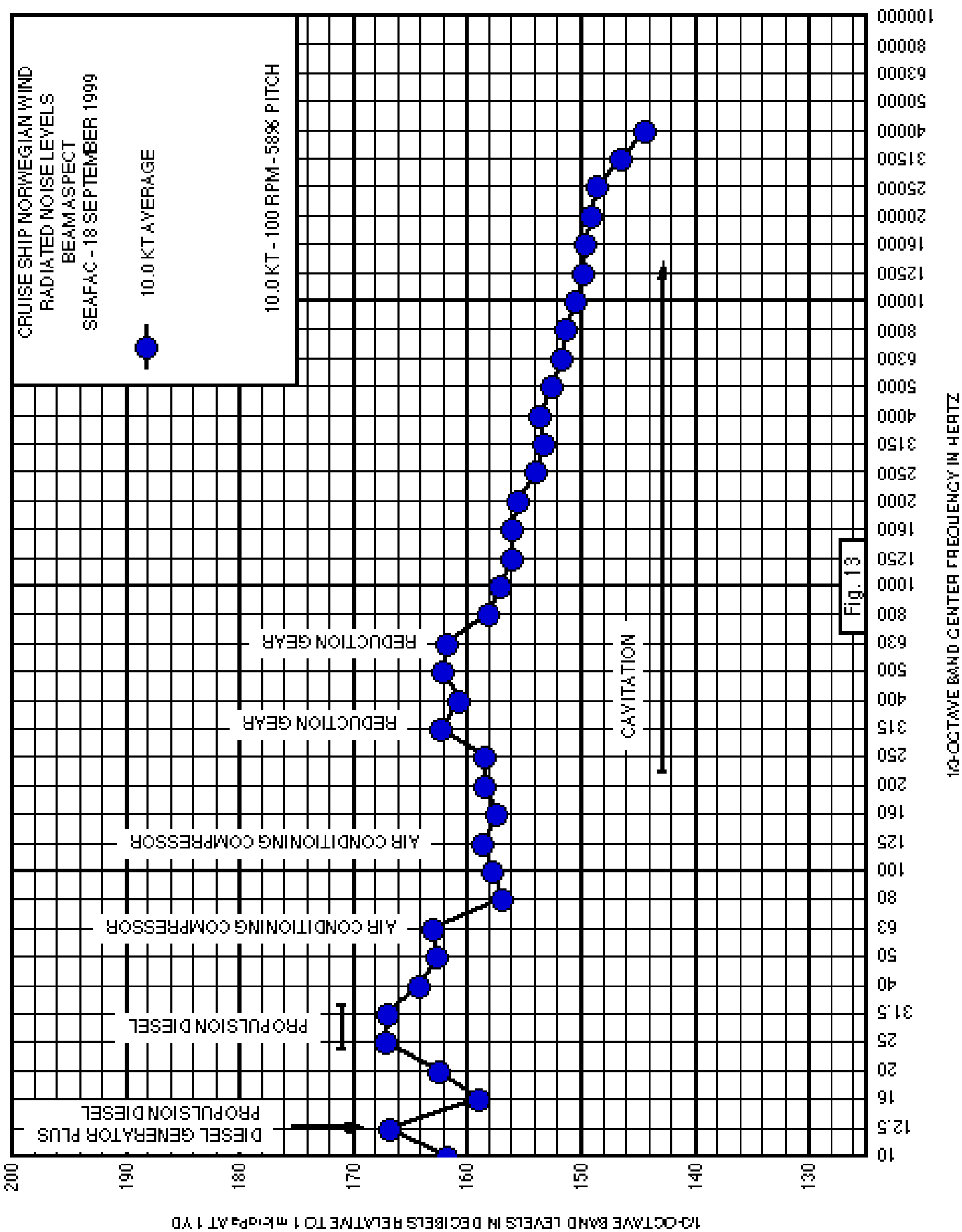


Fig. 13 Norwegian Wind – 10 knots

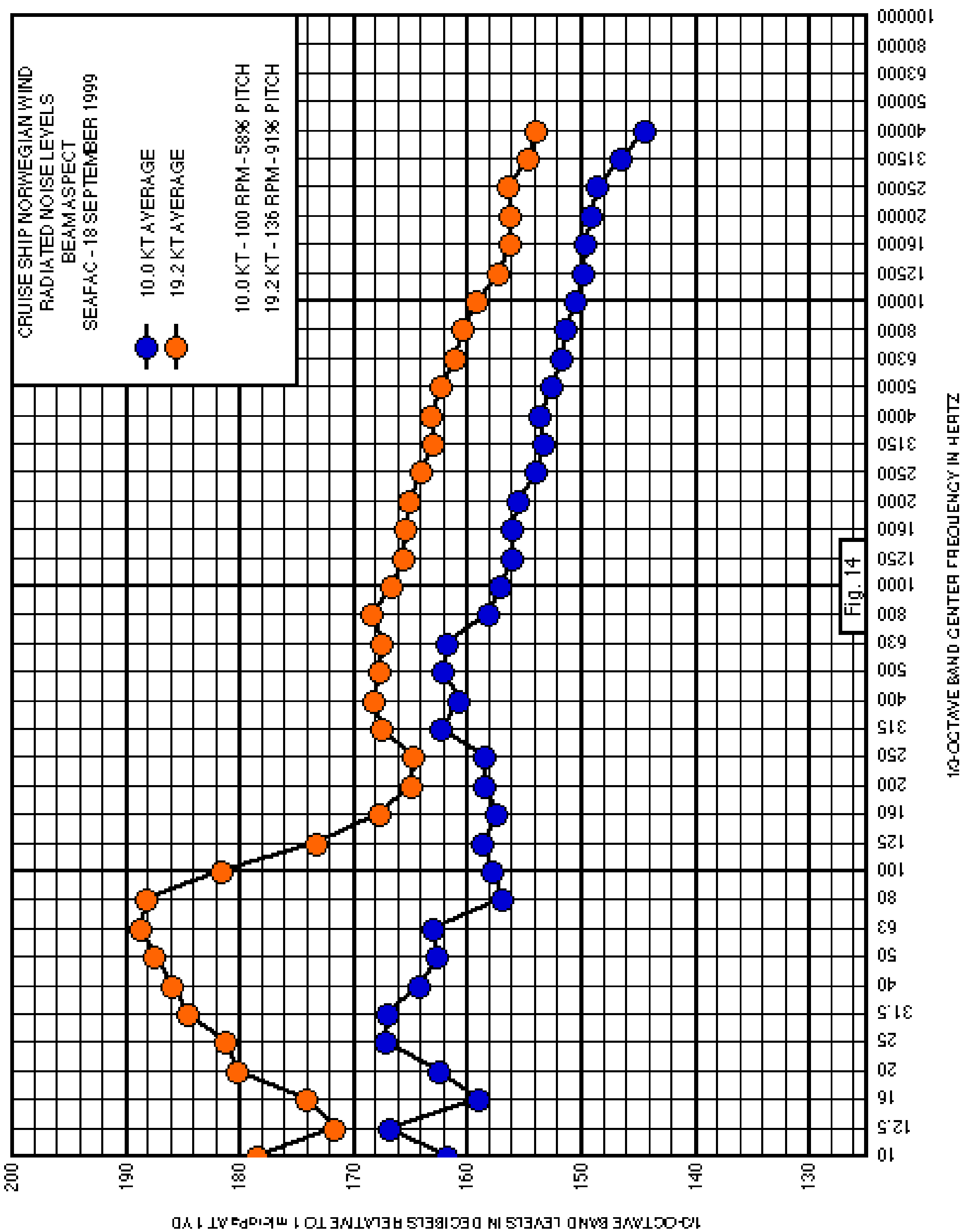


Fig. 14 Norwegian Wind – 19 knots

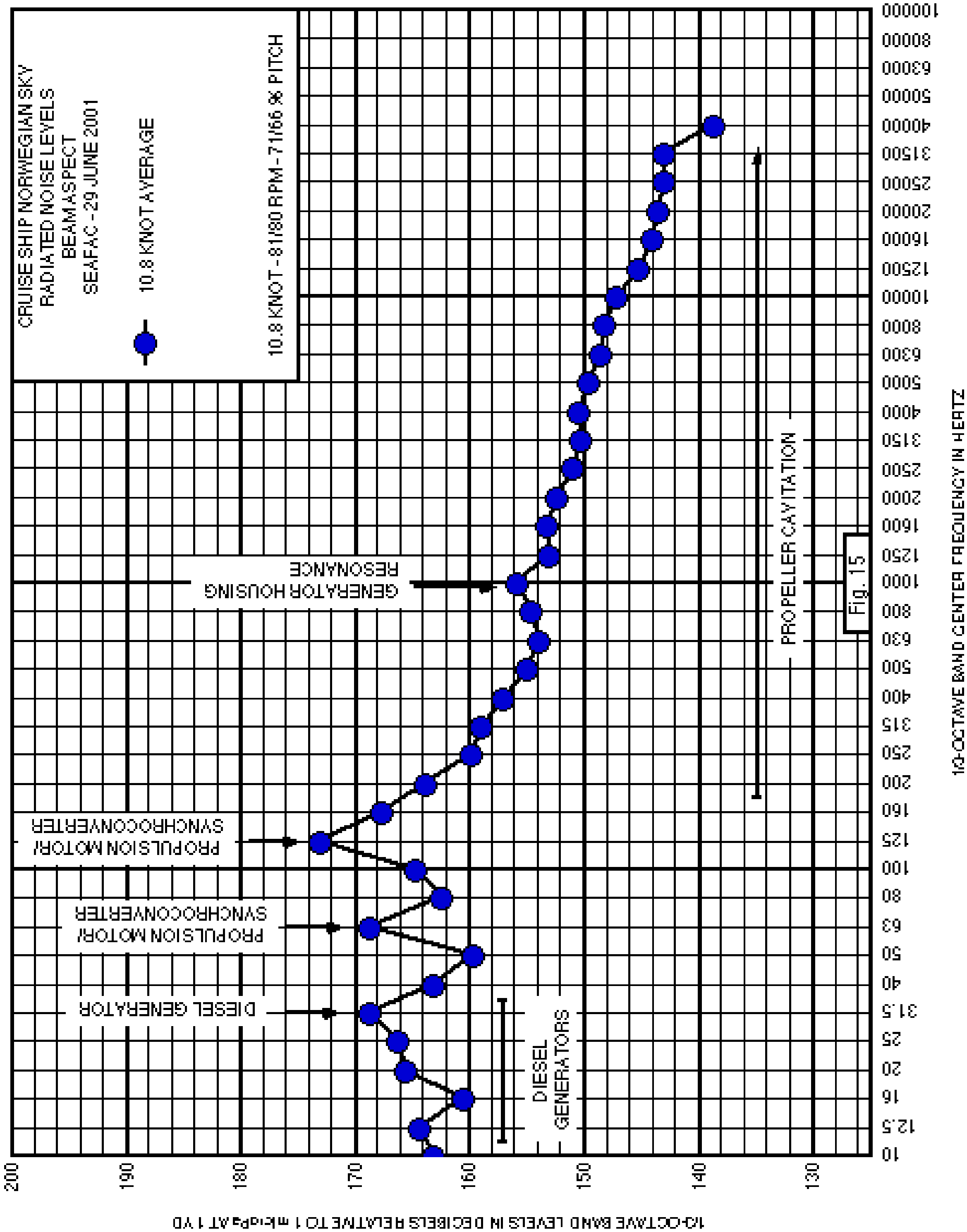


Fig. 15 Norwegian Sky – 10 knots

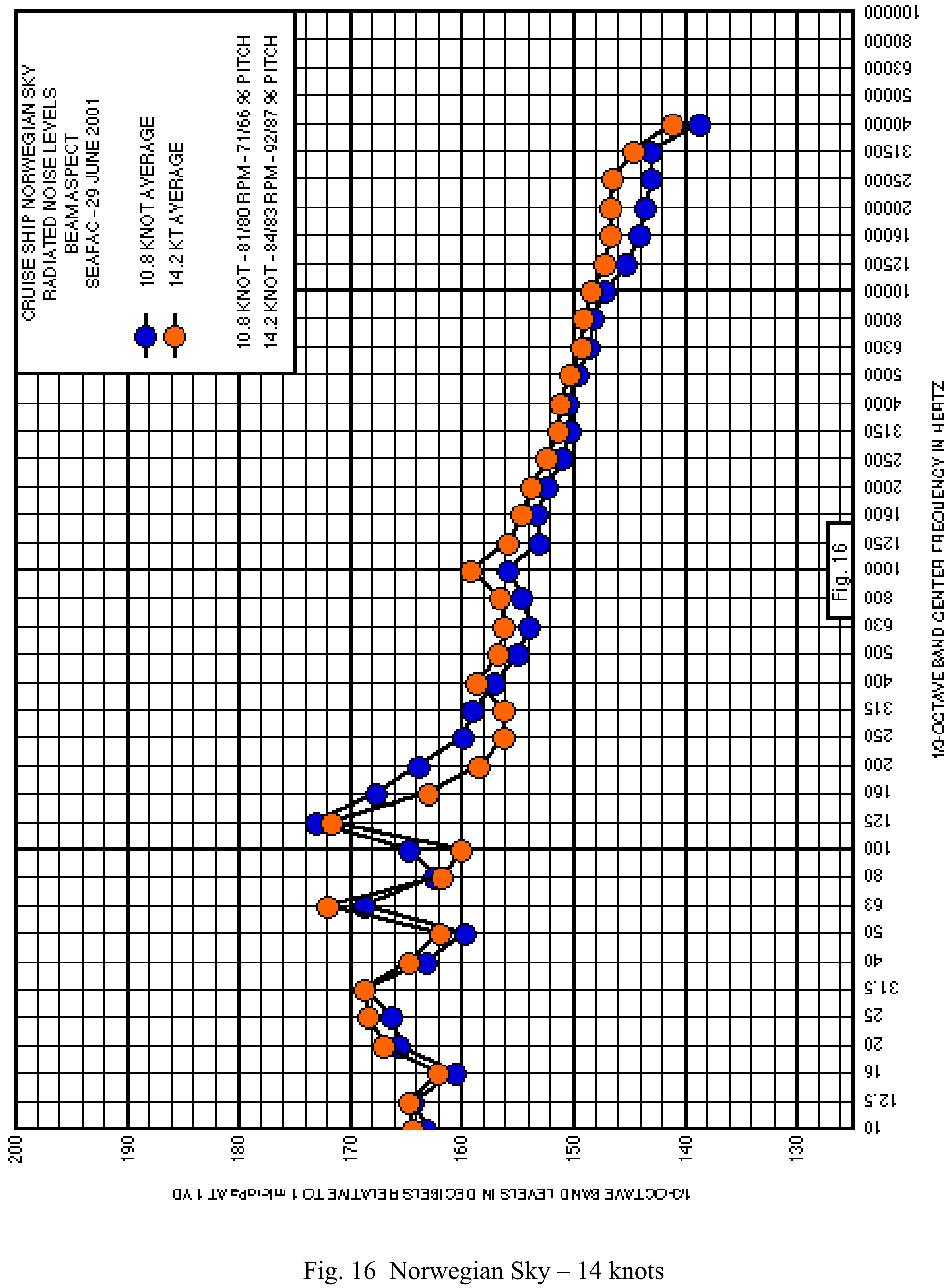


Fig. 16 Norwegian Sky – 14 knots

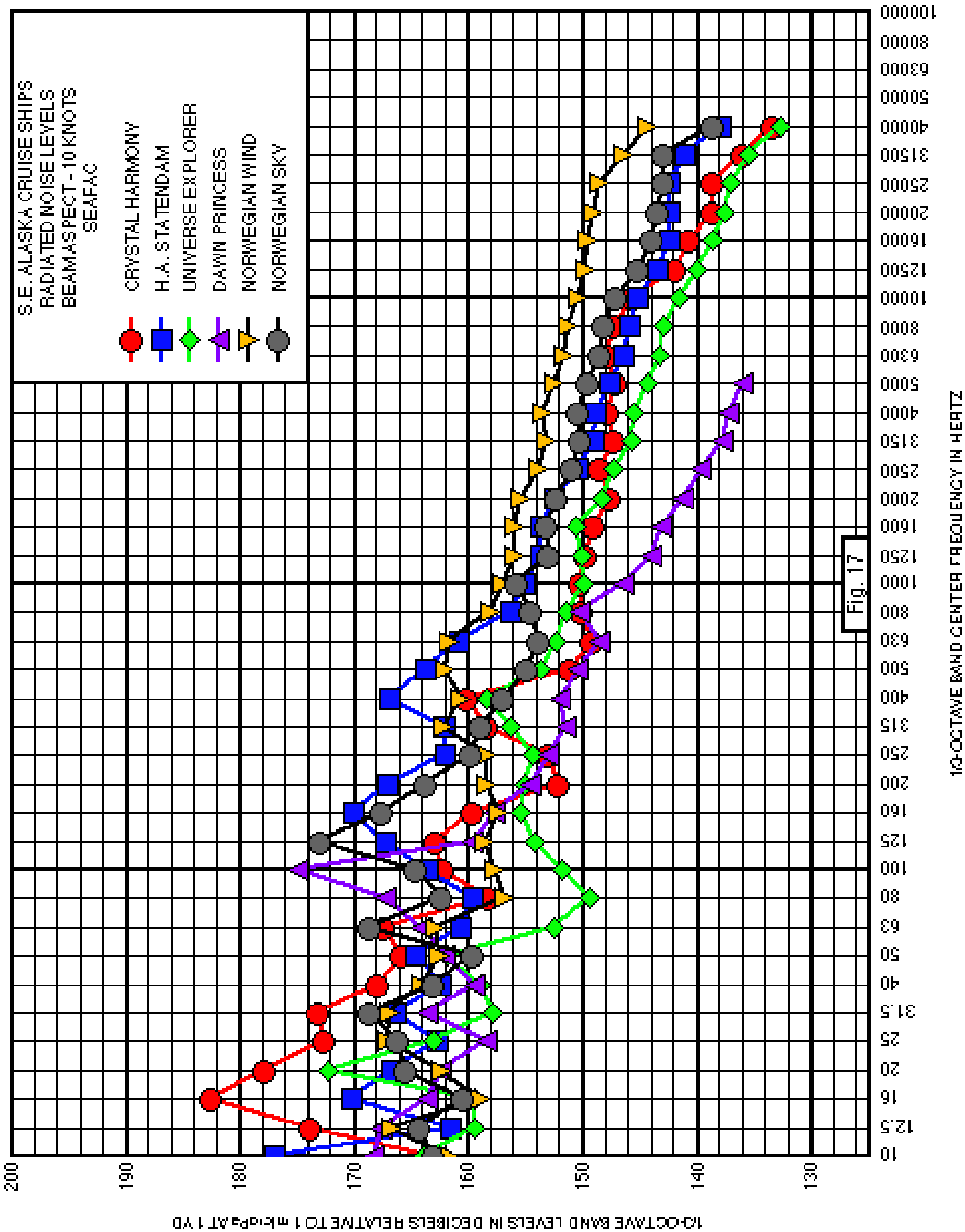


Fig. 17 All Ships – 10 knots

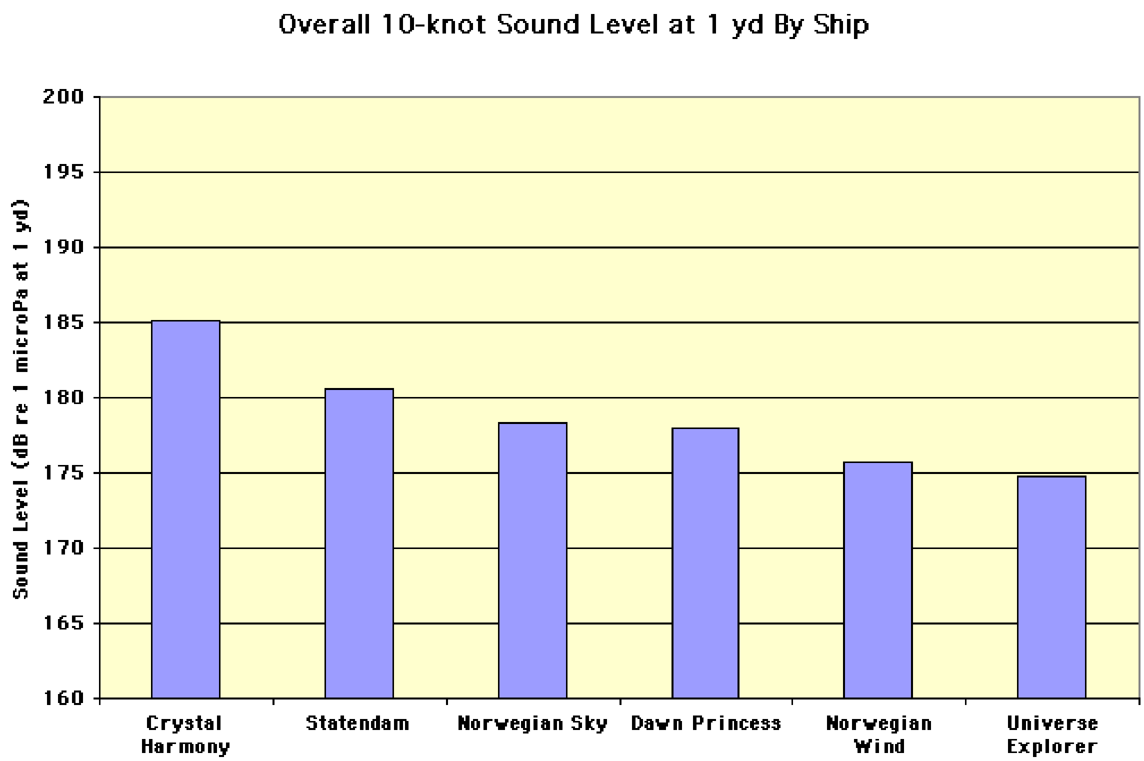


Fig. 18 Overall Sound Levels – All Ships – 1 yd – 10 knots

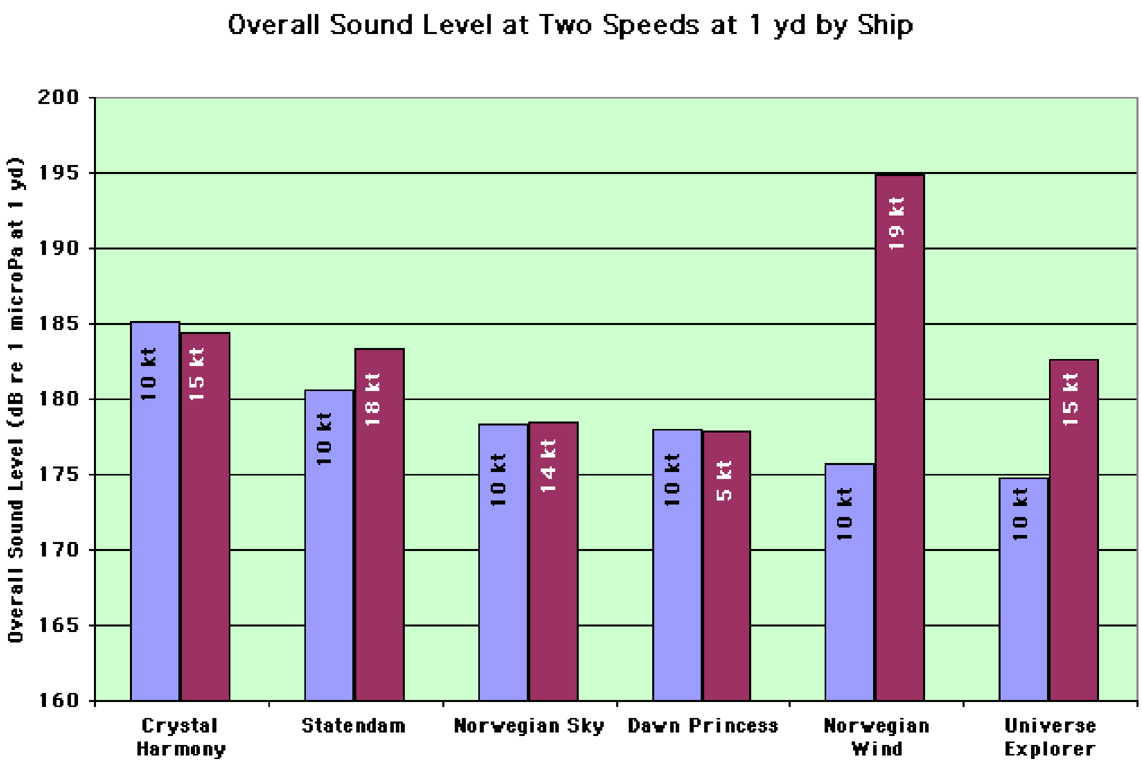


Fig. 19 Overall Sound Levels – All Ships – 1 yd – Both Test Speeds

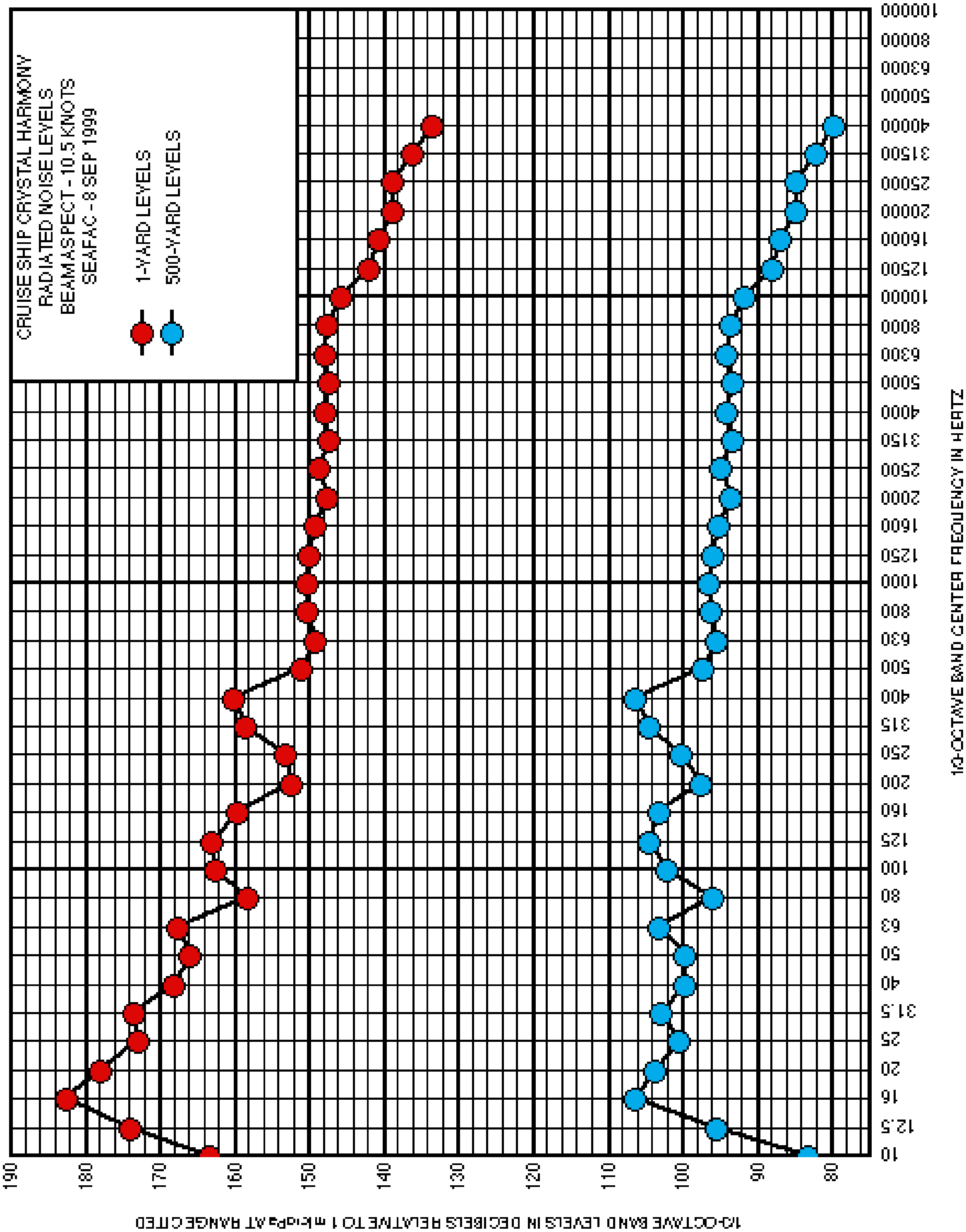


Fig. 20 Example of 1-yard One-Third Octave Levels Vs. 500-yard Levels

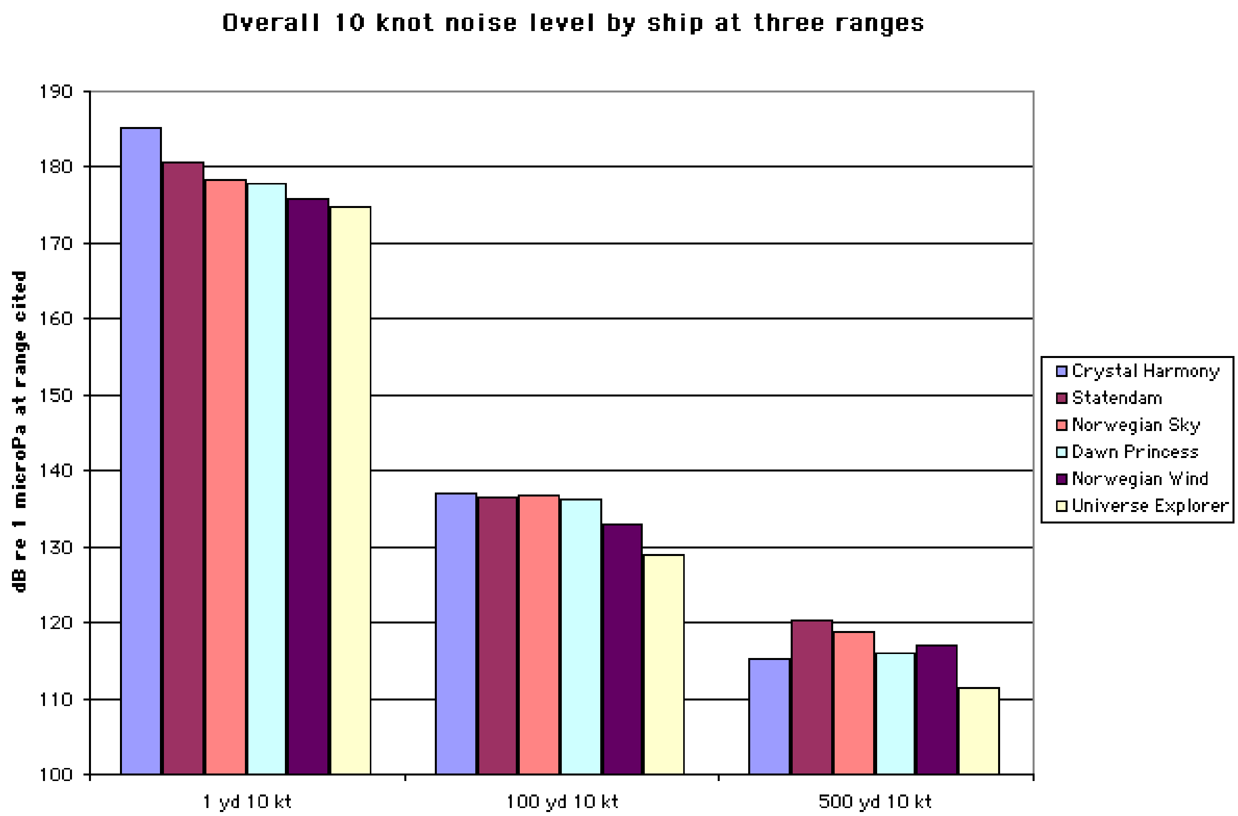


Fig. 21 Overall Sound Level at 10 knots for 1, 100, and 500 yards

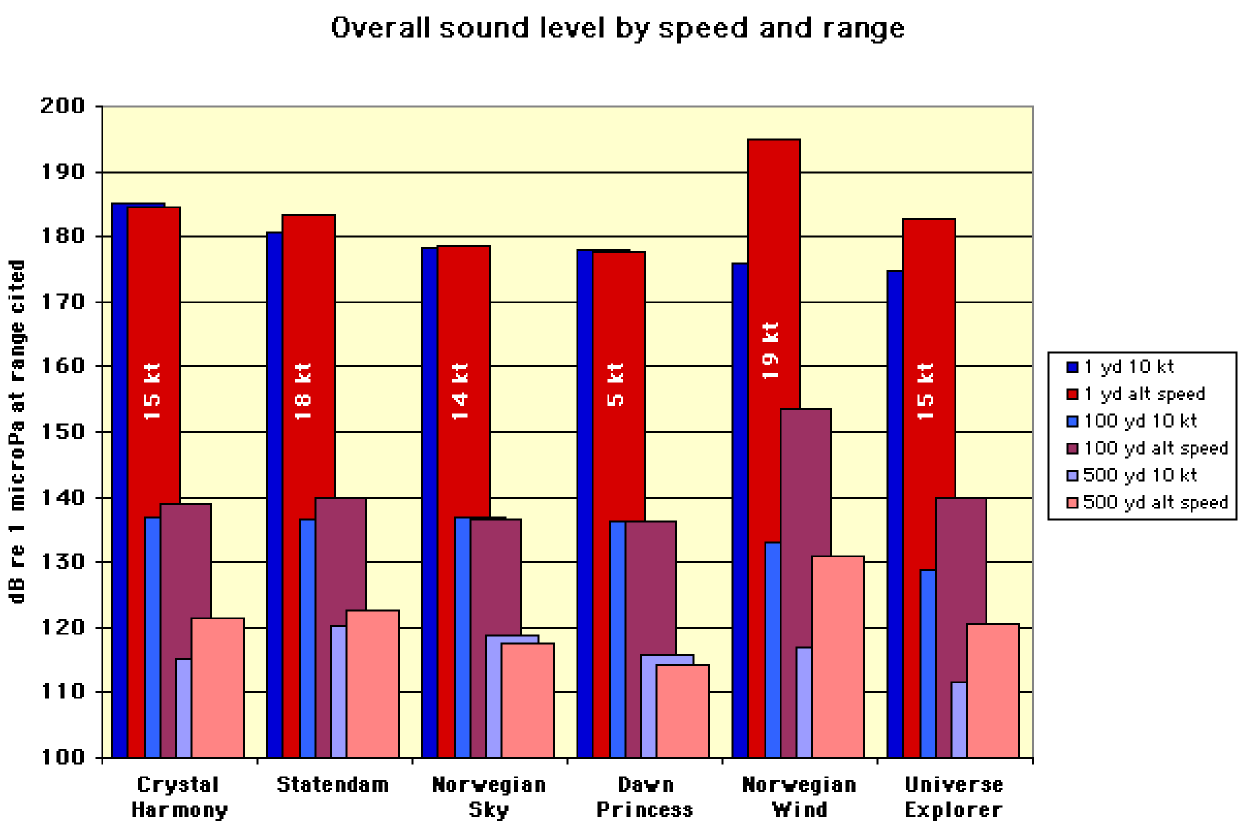


Fig. 22 Overall Sound Level by Ship –
10 knots and Alternate Speed for 1, 100, and 500 yards

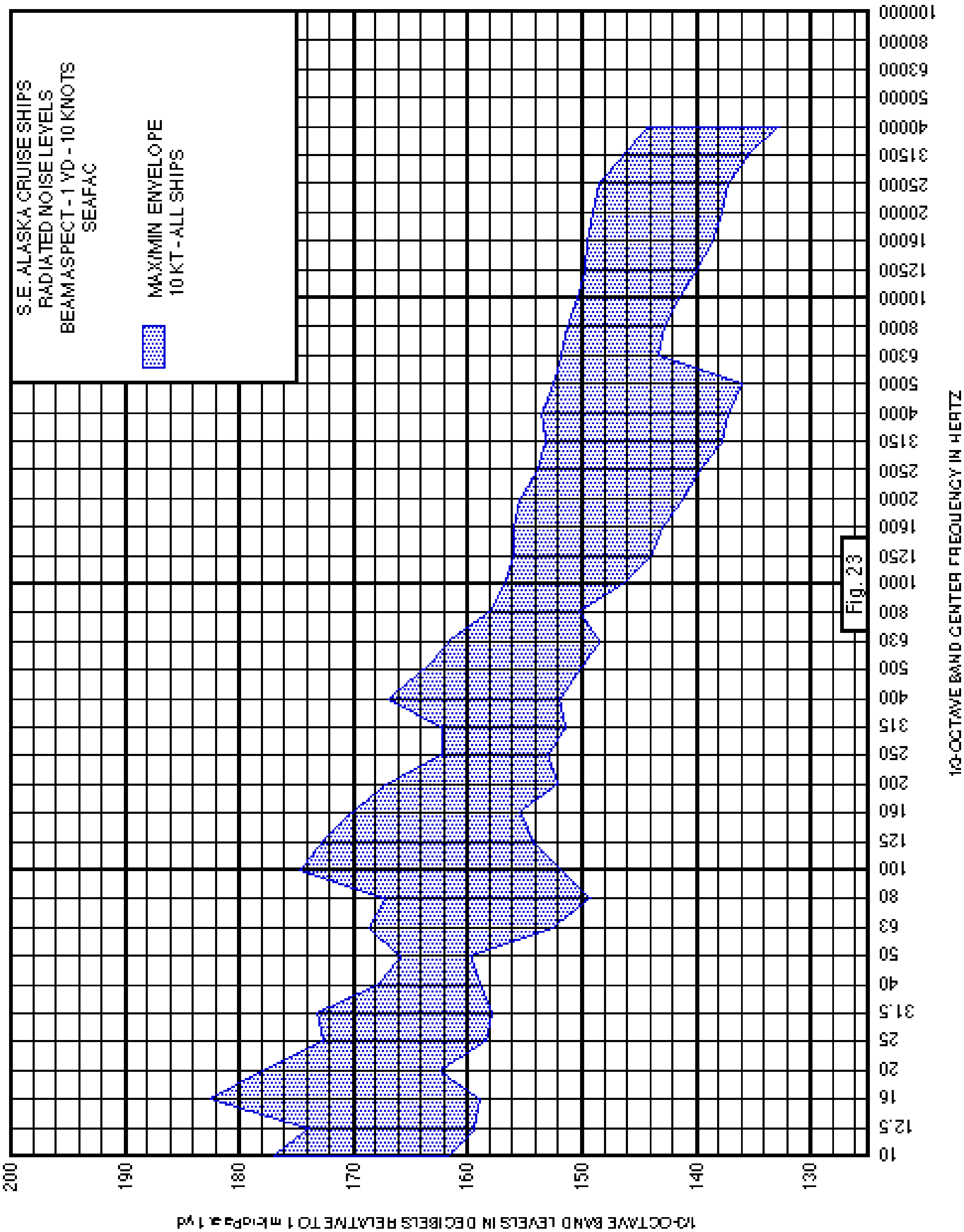


Fig. 23 Max/Min Envelope – 10 knots

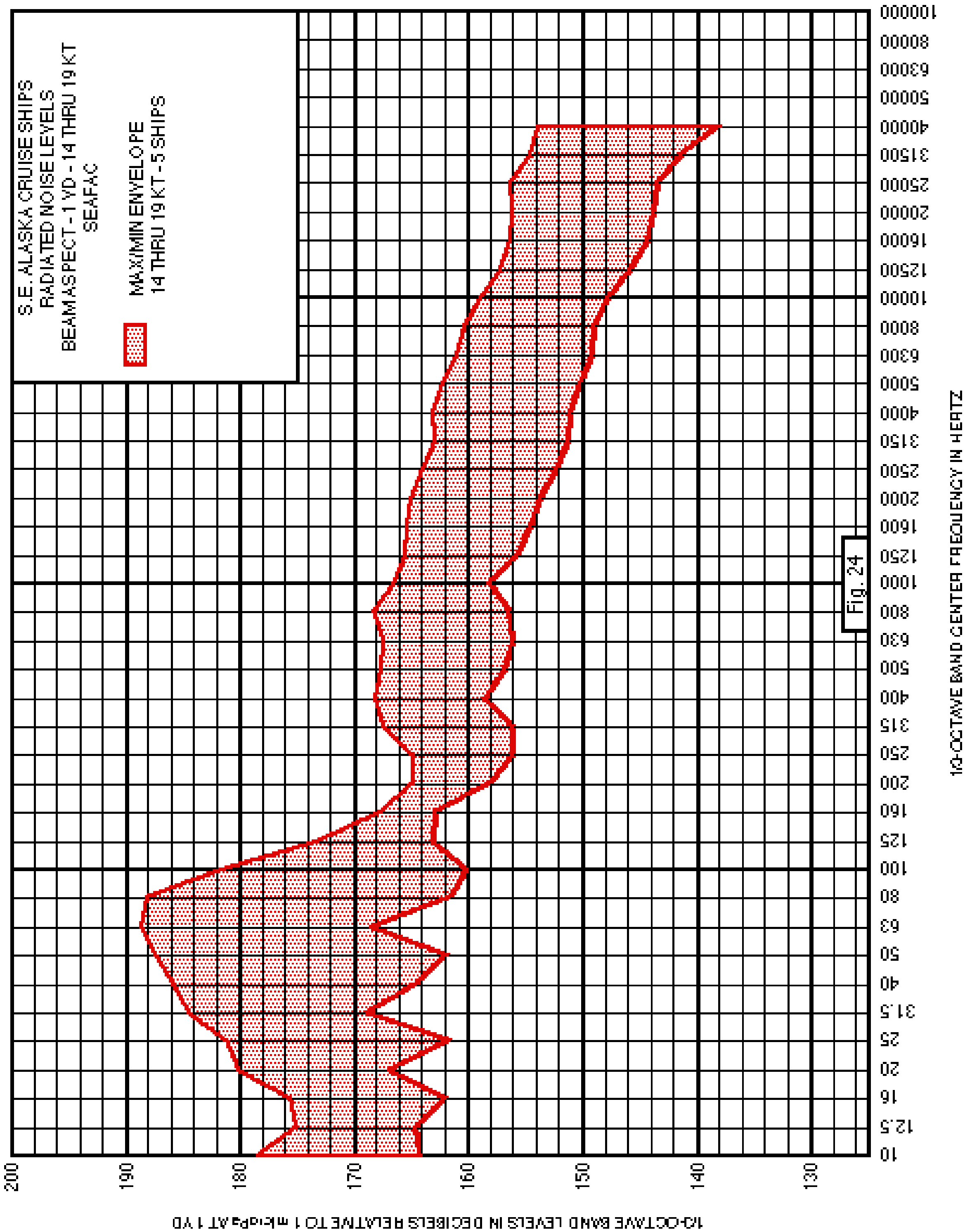


Fig. 24 Max/Min Envelope – 14 Through 19 knots

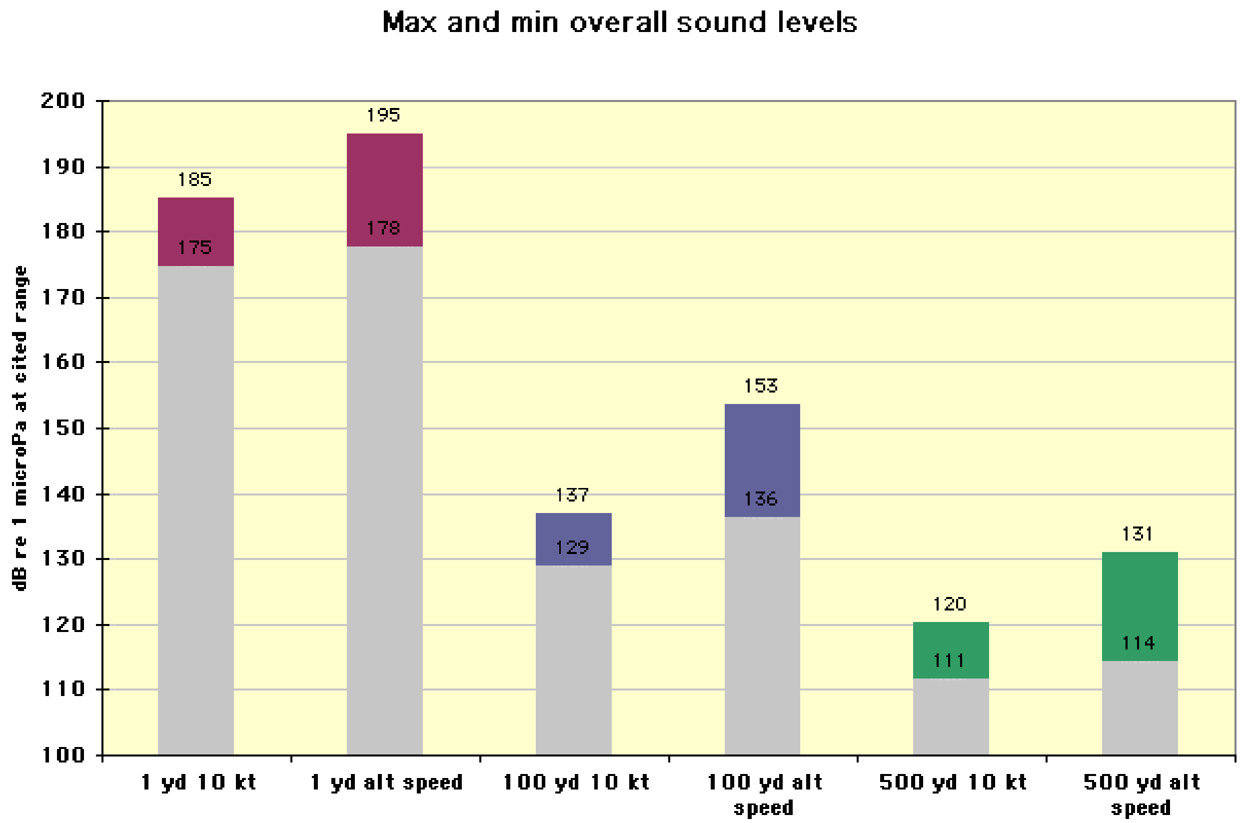


Fig. 25 Maximum and Minimum Overall Sound Level for 1, 100, and 500 yards

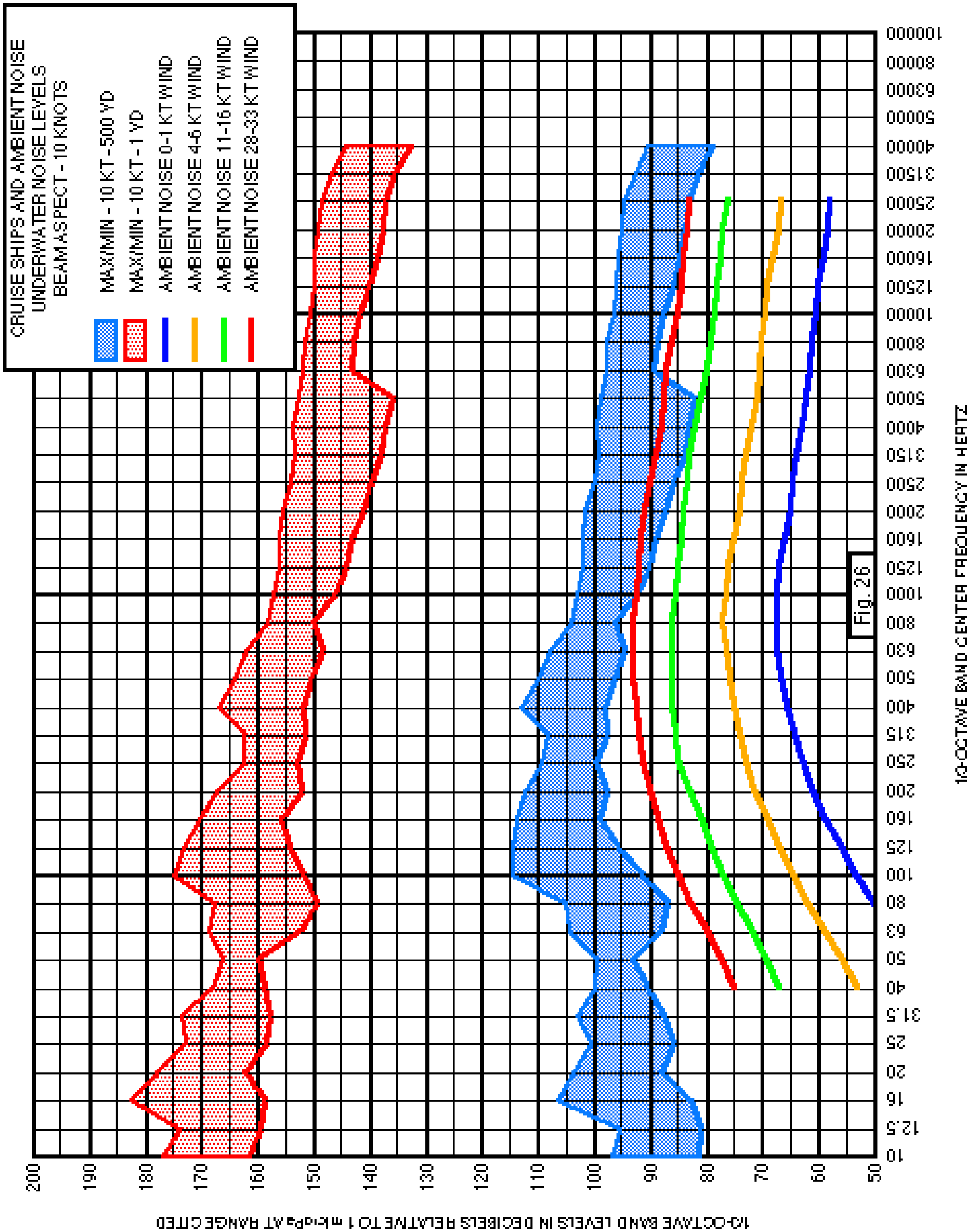


Fig. 26 Cruise Ships and Ambient Noise

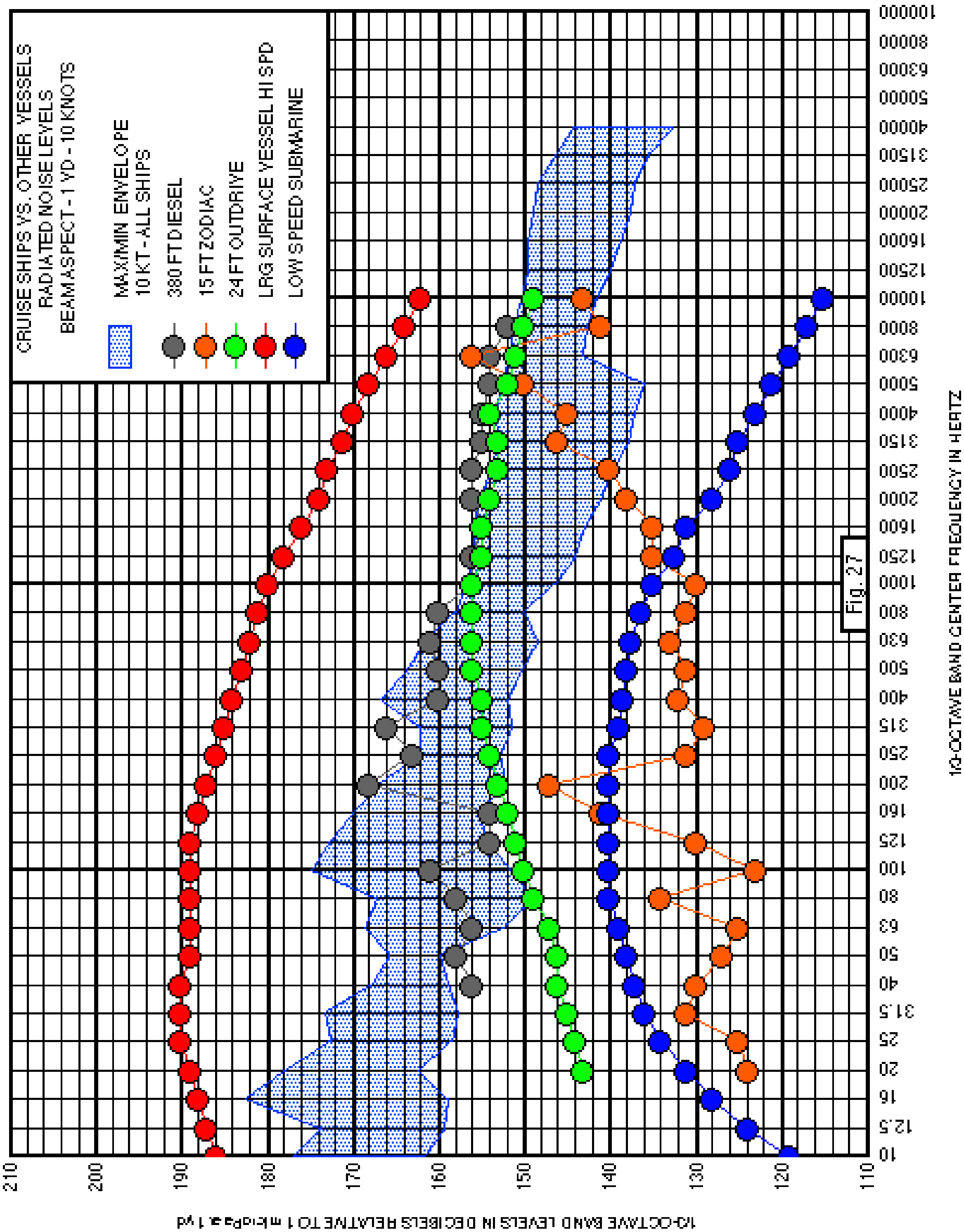
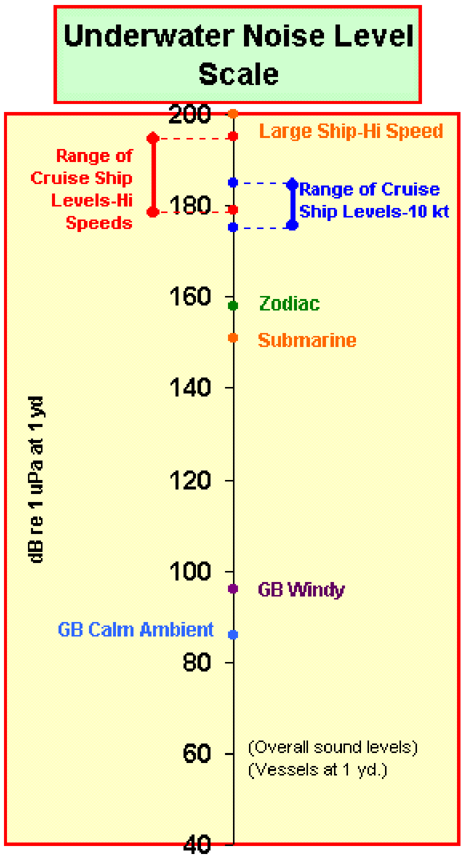
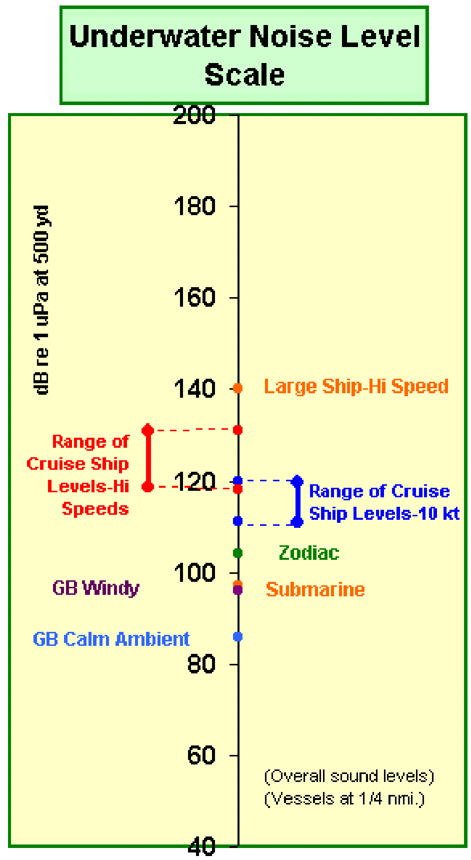


Fig. 27 Cruise Ships and Other Vessels



At 1 yard



At ¼ nautical mile

Fig. 28 Underwater Noise Scale - Overall Sound Levels at Two Distances

REFERENCES

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(2) CDNSWC Ltr 7103/00410/99, Cruise Ship Crystal Harmony – Underwater Acoustic Signature Characterization (Oct 1999).
(3) CDNSWC Ltr 7103/00409/99, Cruise Ship Holland America Statendam – Underwater Acoustic Signature Characterization (Oct 1999).
(4) CDNSWC Ltr 7103/00116/00, Forwarding Additional Holland America Statendam Underwater Noise Signature Data (Apr 2000).
(5) CDNSWC Ltr 7103/00407/99, Cruise Ship Universe Explorer – Underwater Acoustic Signature Characterization (Oct 1999).
(6) CDNSWC Ltr 7103/00117/00, Forwarding Additional Universe Explorer Underwater Noise Signature Data (Apr 2000).
(7) CDNSWC Ltr 7103/00411/99, Cruise Ship Dawn Princess – Underwater Acoustic Signature Characterization (Oct 1999).
(8) CDNSWC Ltr 7120/00504/99, Forwarding Additional Dawn Princess Underwater Noise Signature Data (Dec 1999).
(9) Kinns, R., "The Acoustic Characteristics of Dawn Princess", British Aerospace Report D0007/99 (Nov 1999).
(10) CDNSWC Ltr 7103/00408/99, Cruise Ship Norwegian Wind – Underwater Acoustic Signature Characterization (Oct 1999).
(11) CDNSWC Ltr 7103/00124/00, Forwarding Additional Norwegian Wind Underwater Noise Signature Data (Apr 2000).
(12) CDNSWC Ltr 7120/188/2001, Cruise Ship Norwegian Sky Underwater Acoustic Signature (Sep 2001).
(13) Malme, C.I., Miles, and McElroy, "The Acoustic Environment of Humpback Whales in Glacier Bay and Frederick Sound/Stephens Passage, Alaska", BBN Report 4848 (May 1982).
(14) Burdic, W., Underwater Acoustic System Analysis, Prentice-Hall, New Jersey (1984).
(15) Richardson, W., et. al., Marine Mammals and Noise, Academic Press, San Diego, CA (1995).

Appendix A – Additional Ship Information

All ships had two propellers. All ships were equipped with thrusters.

Ship	Displacement (gross tons - thousand)	Length (ft)	Launched	Propulsion Type	Number Propeller Blades	Propeller Pitch	Date Tested at SEAFAC
Crystal Harmony	49	790	1995	Diesel-Electric	4	Variable	5 September 1999
Holland America Statendam	55	720	1993	Diesel-Electric	4	Variable	7 September 1999
Universe Explorer	23	617	1958	Steam Turbine	4	Constant	8 September 1999
Dawn Princess	77	856	1997	Diesel-Electric	6	Constant	9 September 1999
Norwegian Wind	50	754	1998	Diesel Direct	4	Variable	18 September 1999
Norwegian Sky	77	853	1999	Diesel-Electric	4	Variable	29 June 2001

Crystal Harmony

-Four 8-cylinder 4-cycle turbocharged diesel engines operating at 400 rpm, 8400 kW each
- Engines 1, 2, and 3 operating at SEAFAC
-Two main propulsion electric motors, 12,500 kW each max, ABB Stromberg
- Constant frequency AC power at 60 Hz
- Motor generator used to “regenerate” 60 Hz AC power
- Cycloconverter is 6 pulse type, input frequency = 60 Hz, output frequency = 12.4 Hz at 93 rpm
- SCRs used in all frequency converters including cycloconverters
- Skewed propeller blade design

Holland America Statendam

- Three 8-cylinder diesel generators operating at 512 rpm, 5760 kW each
- Two 12-cylinder diesel generators operating at 512 rpm, 8640 kW each
- Engines 2, 3 (12-cylinder), and 5 (8-cylinder) operating at SEAFAC
- Motor generator used to “regenerate” 60 Hz AC power
- Cycloconverter input frequency = 60 Hz, output frequency = 14 Hz at 140 rpm
- Air conditioning plants operate at 3574 rpm
- Skewed propeller blade design

Universe Explorer

- Three Foster Wheeler 600 psi water tube boilers, fuel oil fired with forced air blowers
- Two boilers operating at SEAFAC
- Two General Electric cross-compound geared propulsion steam engines, 25,500 HP each
- Turbine rpm = 6800 at max shaft speed of 126 rpm
- Reduction gear ratio approximately 54:1
- Three General Electric turbogenerators, 1250 kW each, 10,500 rpm turbine, 1200 rpm generator
- Two generators operating at SEAFAC
- Unskewed propeller design

Dawn Princess

- Four 16-cylinder turbocharged diesel engines operating at 514 rpm, 11,520 kW each
- Two inboard engines operating at SEAFAC
- Propulsion transformers convert 6.6 kV from generators to 2.2 kV AC.
- Synchroconverter (12-pulse) input frequency = 60 Hz, output frequency = 16.92 Hz at 145 rpm. Synchroconverter converts 2.2 kV AC to DC, then to AC at frequency required for propulsion motor.
- Equipped with stabilizers to control ship motion in heavy seas
- Air conditioning plants operate at 3575 rpm
- Skewed propeller blade design

Norwegian Wind

- Two father-son diesel engine complexes
- Each complex: 8-cylinder turbocharged diesel and 6-cylinder turbocharged diesel clutched to reduction gear, 18,480 kW
- At 10 knots: two outboard (8-cylinder) diesel engines online
- At 19.2 knots: all four engines online
- Reduction gear: 1:4.7
- Electrical power: two 8-cylinder diesel engines at 720 rpm
- Air conditioning plants operate at 3555-3560 rpm

Norwegian Sky

- Three 7-cylinder turbocharged diesel generators operating at 400 rpm, 9100 kW each
- Three 6-cylinder turbocharged diesel generators operating at 400 rpm, 7800 kW each
- Two generators operating at SEAFAC during 10 and 14 knot tests
- CEGELEC AEG synchroconverter input frequency = 60 Hz, output frequency = 18 Hz at 135 rpm
- Air conditioning plants operate at 3575 rpm
- Skewed propeller blade design

Appendix B – Test Conditions – Additional Information

Crystal Harmony – 5 September 1999 – 6 am to 8:30 am

Test ID	Ship Speed (kt)	Ship Heading	Shaft rpm (Port/Stbd)	Propeller Pitch (Port/Stbd) (degrees)	CPA Distance (yd)	Comments
1	15.3	N	93/90	29.0/29.4	400	
2	15.4	S	92/92	29.4/29.4	400	
3	10.6	N	64/63	29.4/29.4	470	
4	~10	S	64/63	29.5/29.4	>400	Tracking system failure
5	10.5	S	64/63	29.5/29.3	490	

Holland America Statendam – 7 September 1999 – 2:30 am to 5:00 am

Test ID	Ship Speed (kt)	Ship Heading	Shaft rpm (Port/Stbd)	Propeller Pitch (Port/Stbd) (percent)	CPA Distance (yd)	Comments
1	18.1	N	113/113	67/72	508	
2	17.9	S	113/112	62/67	473	
3	10.7	N	85/79	31/31	525	
4	10.9	S	85/79	30/30	508	

Universe Explorer – 8/9 September 1999 – 11 pm to 1 am

Test ID	Ship Speed (kt)	Ship Heading	Shaft rpm	Propeller Pitch	CPA Distance (yd)	Comments
1	15.8	N	84	Fixed	489	
2	15.1	S	84	Fixed	497	
3	10.0	N	54	Fixed	463	
4	9.9	S	54	Fixed	517	

Dawn Princess – 9 September 1999 – 7:30 pm to 10:30 pm

Test ID	Ship Speed (kt)	Ship Heading	Shaft rpm	Propeller Pitch	CPA Distance (yd)	Comments
1	10.0	N	67	Fixed	511	
2	9.8	S	67	Fixed	526	
3	5.7	N	40	Fixed	470	
4	5.4	S	40	Fixed	471	

Norwegian Wind – 18 September 1999 – 5:30 am to 8:30 am

Test ID	Ship Speed (kt)	Ship Heading	Shaft rpm (Port&Stbd)	Propeller Pitch (Port&Stbd) (percent)	CPA Distance (yd)	Comments
1	19.4	N	136.4	91	464	
2	18.9	S	136.4	91	298	CPA too close
3	19.4	N	136.4	92	525	
4	11.0	S	99.5	63	512	
5	10.1	N	99.9	58	490	
6	9.9	S	99.8	58	490	

Norwegian Sky – 29 June 2001 – 1:30 am to 4:00 am

Test ID	Ship Speed (kt)	Ship Heading	Shaft rpm (Port&Stbd)	Propeller Pitch (Port/Stbd) (percent)	CPA Distance (yd)	Comments
1	14.2	N	82	91/86	453	
2	14.2	S	82	91/87	500	
3	10.7	N	79	70/65	440	
4	10.9	S	79	70/65	490	

N – north
S – south
CPA – closest point of approach to the noise measurement array

Appendix C - Discussion of Noise Levels and Noise Intensity

When assessing the significance of underwater noise levels, it is essential to recognize that underwater and in-air noise levels are measured on different scales and that in-water noise levels represent different sound intensities than in-air noise levels. This means that the sound intensity of a 100 decibel (dB) noise in air is not equal to that of a 100 dB noise in water. Interpreting underwater noise levels based on more familiar in-air decibel levels will result in erroneous conclusions. This appendix contains additional discussion of in-air versus in-water noise decibel levels.

This difference in noise scales arises from two sources. First, the reference pressures that are used for in-air and in-water measurements are different. By convention, the in-air reference pressure is 20 microPascals and the in-water reference pressure is 1 microPascal. Use of different reference pressures leads to a difference of 26 dB between the in-air and in-water scales. However, an additional factor also comes into play.

When comparing acoustic intensities between air and water the difference between the acoustic properties of the two mediums is also important. Taking both the difference in reference pressures and the acoustic properties (density and sound speed) of air and water into account, the difference in the in-water and in-air dB scales becomes about 60 dB. Thus, if two sounds of equal intensity occur in air and water, the dB value for the underwater sound will be 60 dB higher than the dB value for the airborne sound.

Example:
A 0 dB (re 20 μPa) sound in air (at 1 kHz) is just barely perceptible to the human ear. This decibel level corresponds to a sound pressure value of 20 microPascals.

A 20 microPascal pressure in water will be measured at a level of 26 dB re 1 μPa in water, because the standard reference pressures that are used in air and water are different.

Since acoustic intensity is important in terms of the acoustic energy that is perceived, acoustic intensity should also be considered.

A 0 dB (re 20 μPa) sound in air corresponds to an acoustic intensity level of $1\text{x}10^{-12}$ Watts/meter^2.

If a sound of this intensity occurs in water, the corresponding intensity level in water would be 61.7 dB re $6.76\text{x}10^{-19}$ Watts/meter^2, which is the reference intensity that corresponds to 1 μPa in water.

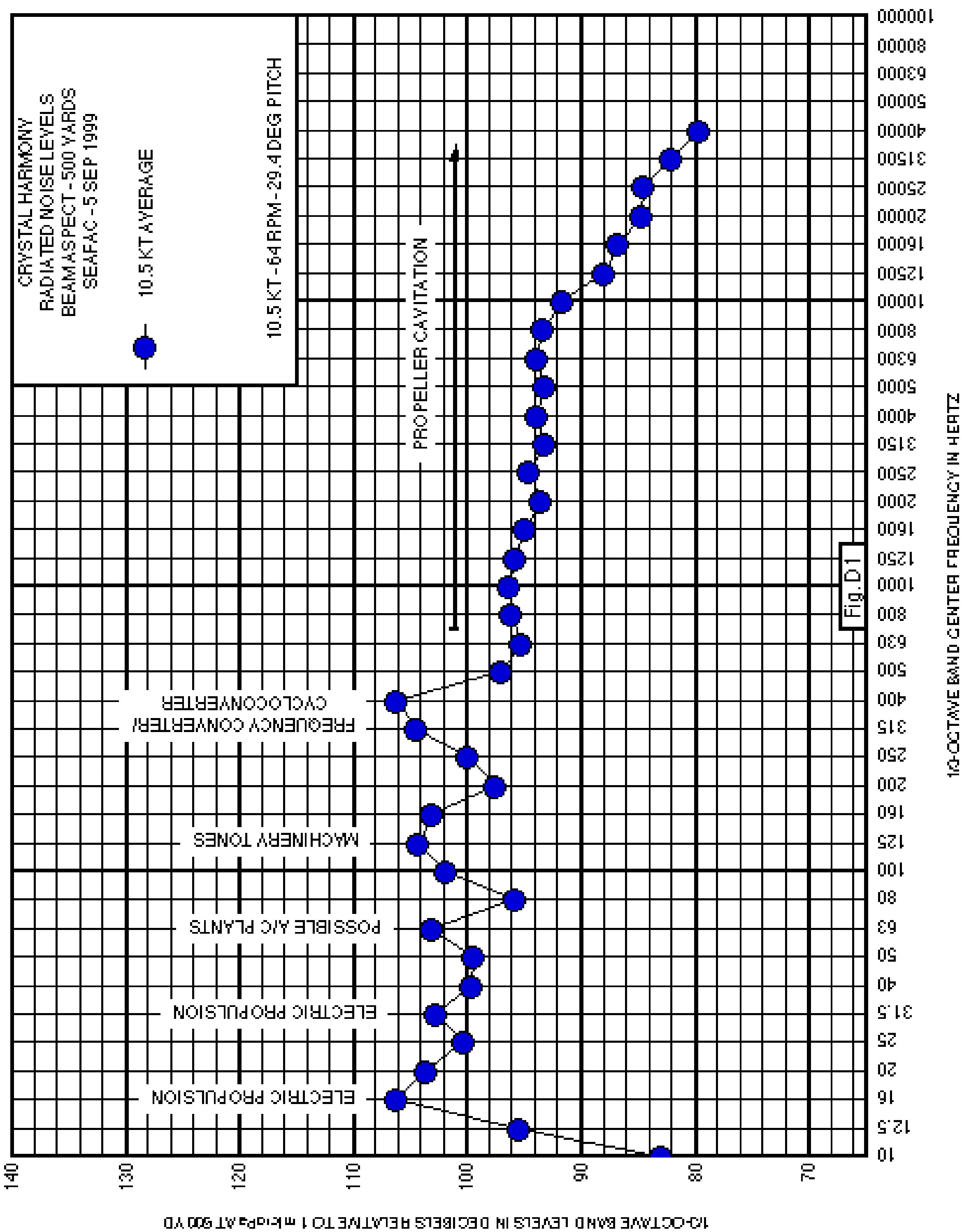
This means that the acoustic power per unit area on the acoustic wavefront of a 120 dB sound in water is about equal to the power per unit area on the wavefront of a 60 dB sound in air. So even though the 120 dB sound in water seems like a high number based on our in-air experience, in terms of power per unit area on the wavefront it is more like a 60 dB sound in air.

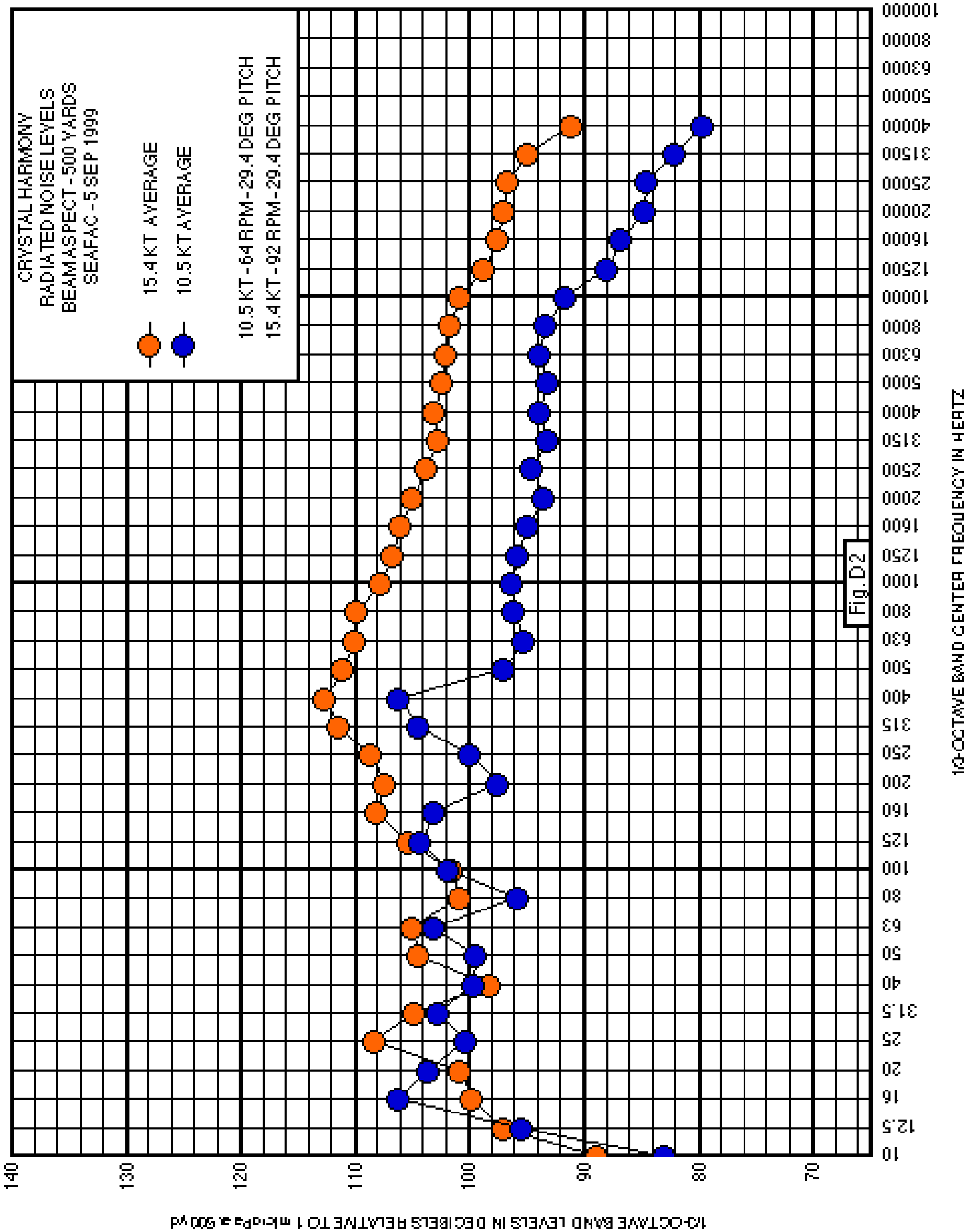
Appendix D – Cruise Ship Noise Spectra at 500 Yards

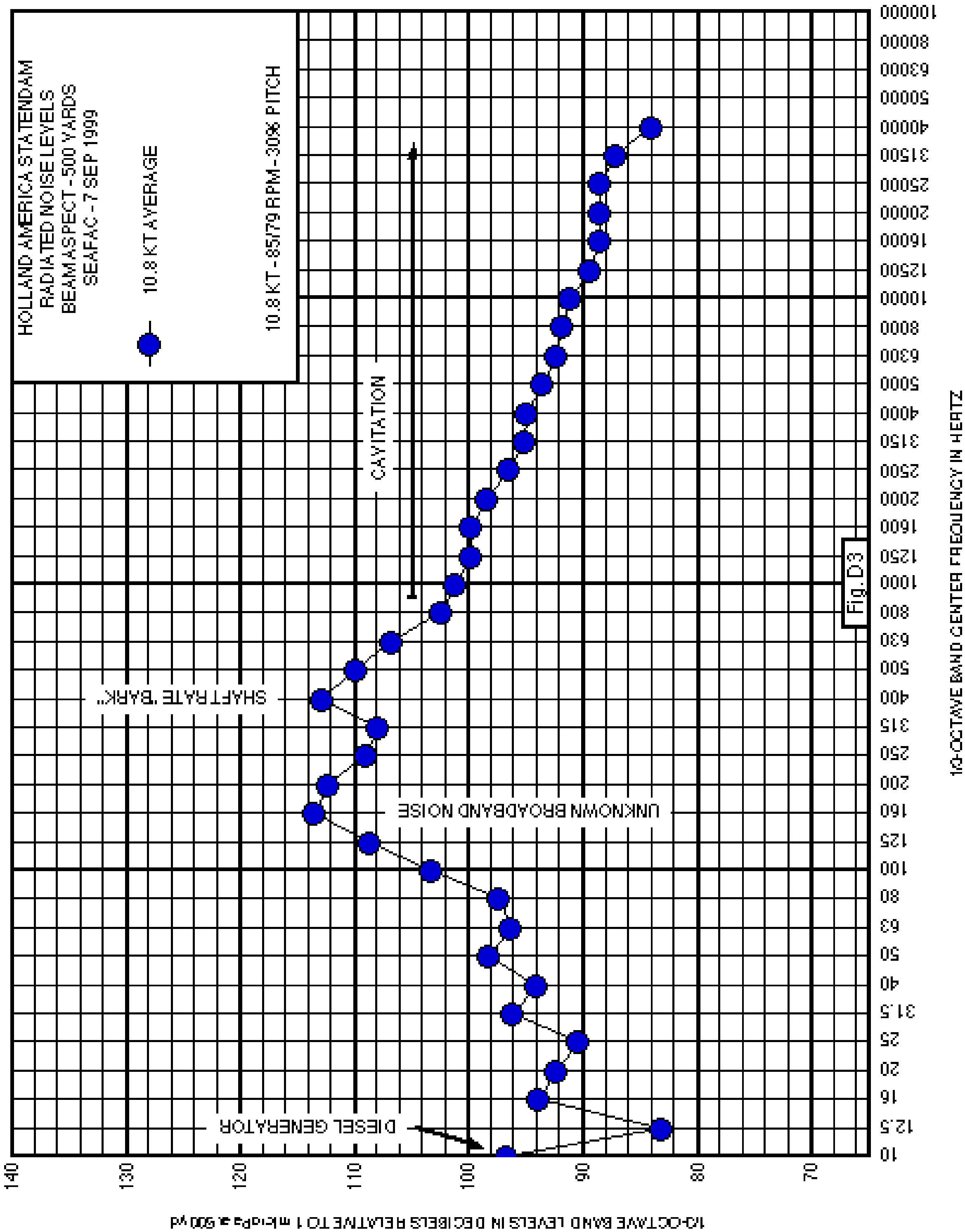
The noise spectra in the body of this report were reported as 1-yard levels. The 1-yard source levels represent the far-field noise levels that would be encountered at 1 yard from the ship, if they could be reliably measured at that location. These levels were inferred from the levels measured at 500 yards. This translation to 1-yard source levels was performed by applying acoustic spherical spreading to the measured levels. Spherical spreading dictates that acoustic intensity diminishes by 20 times the log of the distance from the noise source to the noise measurement point (ref. 1). This factor is called the *range correction factor* because it presumably corrects a measurement made at any distance to an inferred level at a range of 1 yard.

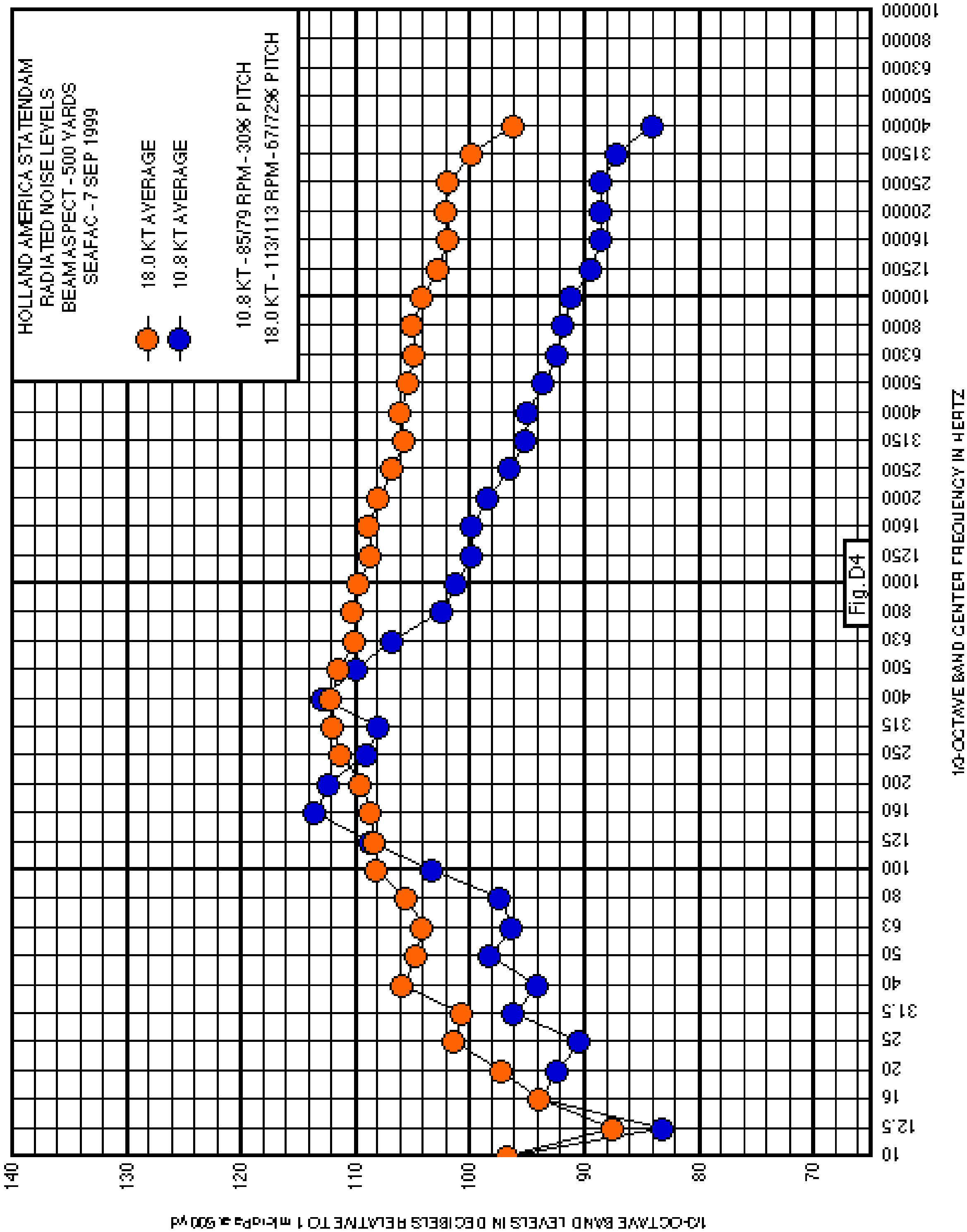
For noise sources at shallow depths multi-path propagation factors that significantly affect low frequency levels were considered. This correction accounts for the differences in the shapes of the 1-yard and 500-yard signatures at low frequencies (in this case, less than 300 Hz).

This appendix provides the one-third octave noise spectra for a range of 500 yards for each cruise ship. These are the spectra that were used to derive the 1-yard spectra and levels that are contained in this report.

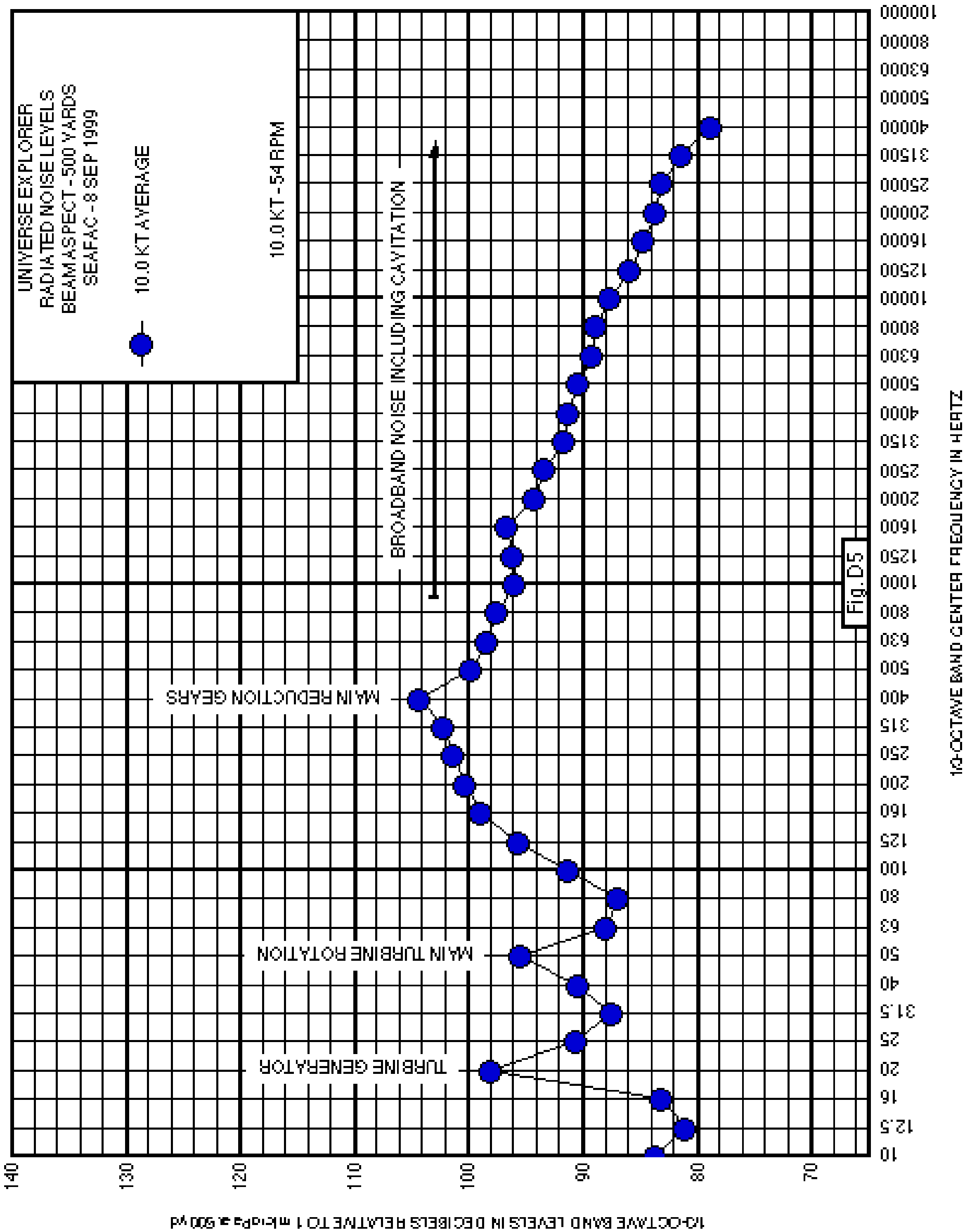

CRYSTAL HARMONY
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 5 SEP 1999
10.5 KT AVERAGE
10.5 KT - 64 RPM - 29.4 DEG PITCH
PROPELLER CAVITATION
FREQUENCY CONVERTER/
CYCLOCONVERTER
MACHINERY TONES
POSSIBLE A/C PLANTS
ELECTRIC PROPULSION
ELECTRIC PROPULSION
Fig. D1
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa AT 500 YD
140
130
120
110
100
90
80
70
10
12.5
16
20
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
12500
16000
20000
25000
31500
40000
50000
63000
80000
100000

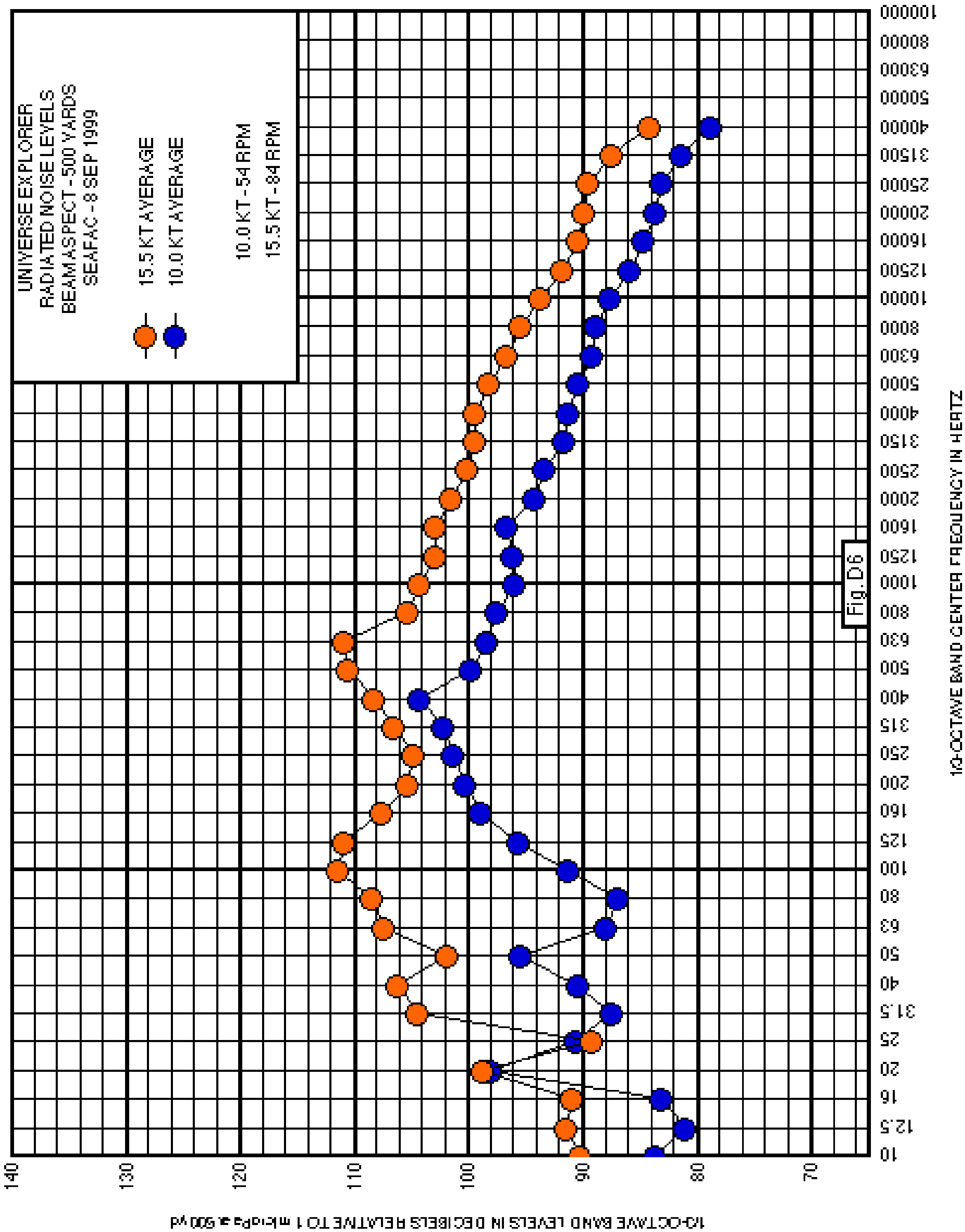

CRYSTAL HARMONY
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 5 SEP 1999
15.4 KT AVERAGE
10.5 KT AVERAGE
10.5 KT - 64 RPM - 29.4 DEG PITCH
15.4 KT - 92 RPM - 29.4 DEG PITCH
Fig. D2
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ

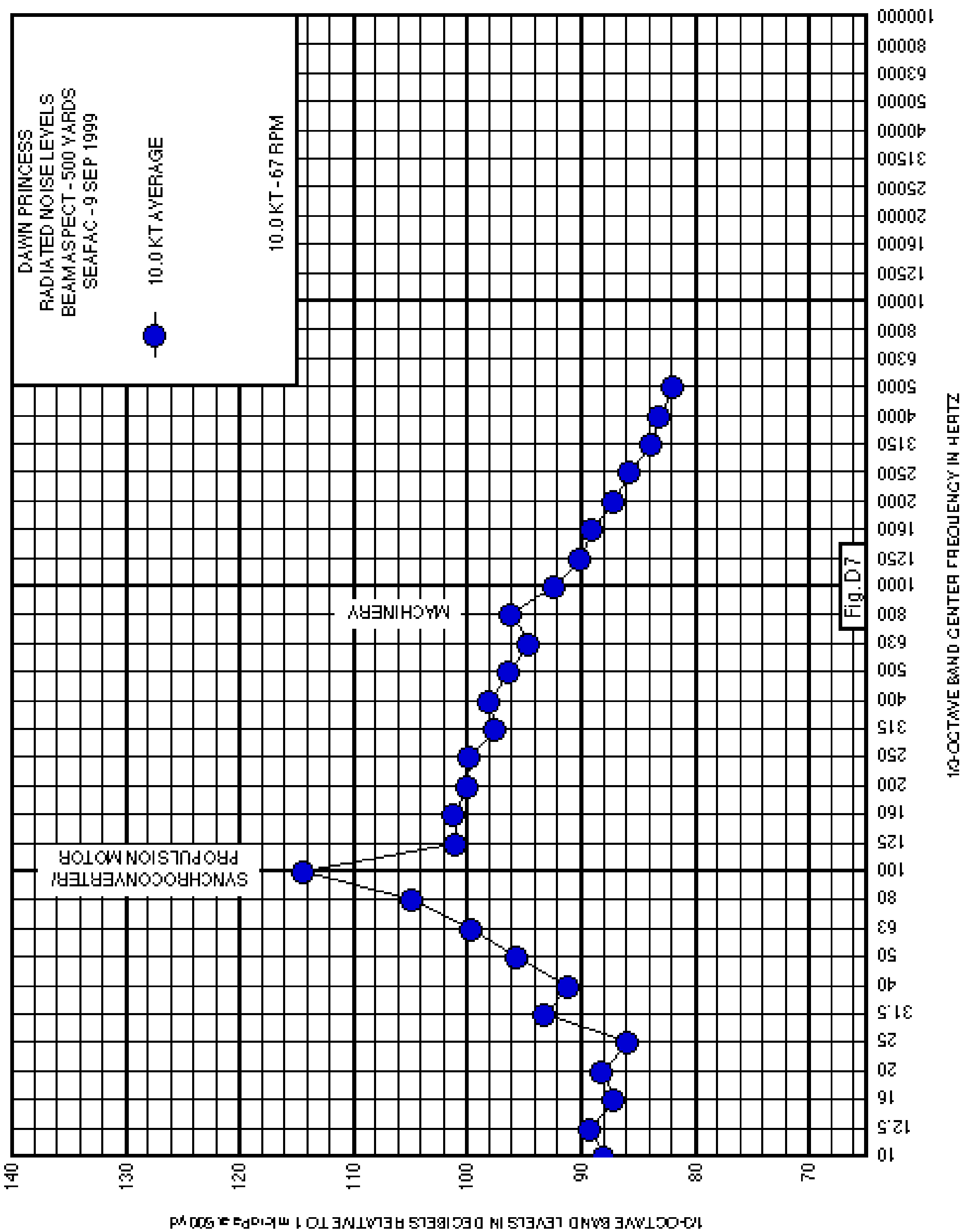

HOLLAND AMERICA STATENDAM
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 7 SEP 1999
10.8 KT AVERAGE
10.8 KT - 85/79 RPM - 30% PITCH
CAVITATION
SHAFT RATE "BARK"
UNKNOWN BROADBAND NOISE
DIESEL GENERATOR
Fig. D3
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd
140
130
120
110
100
90
80
70
10
12.5
16
20
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
12500
16000
20000
25000
31500
40000
50000
63000
80000
100000

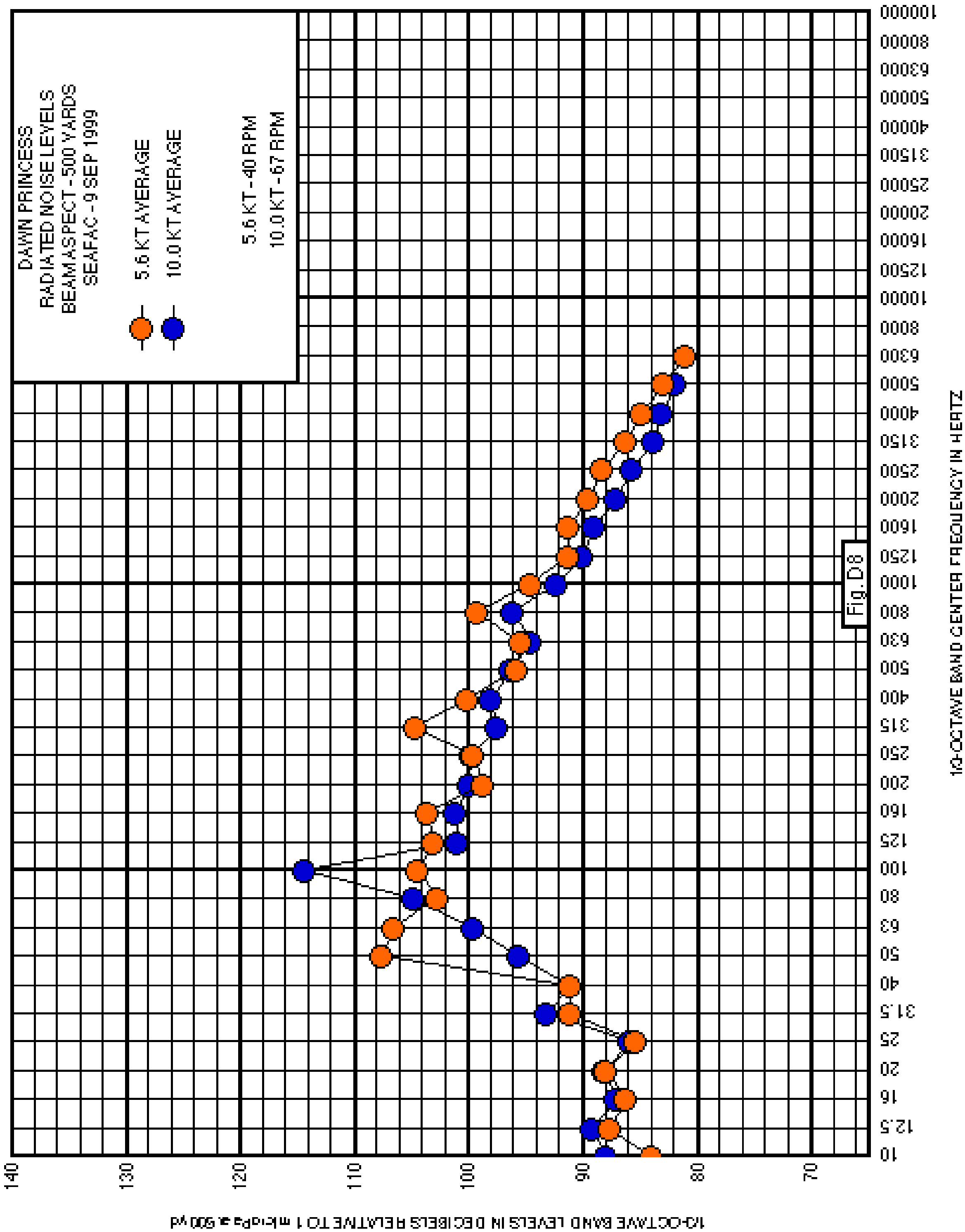


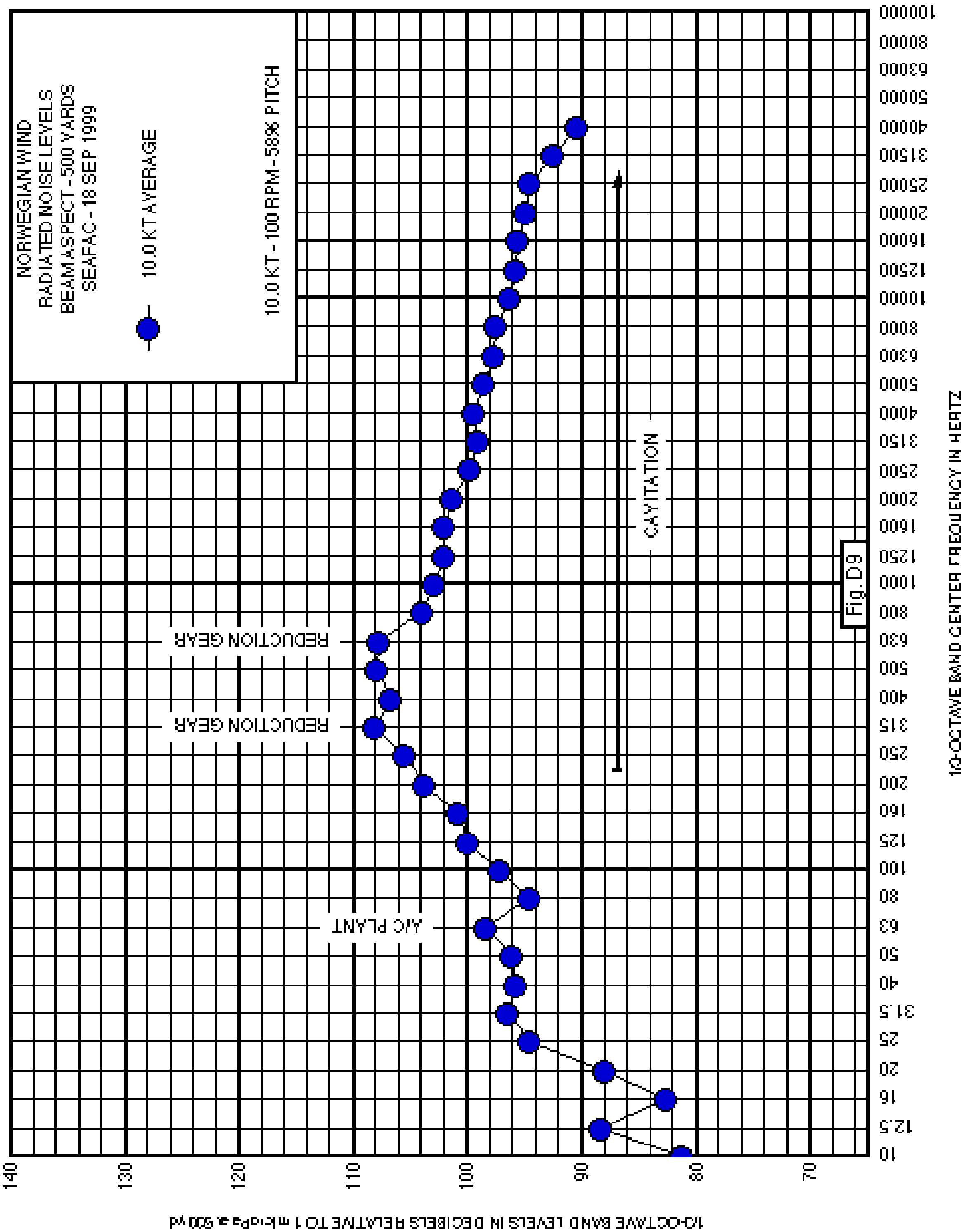
HOLLAND AMERICA STATENDAM
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 7 SEP 1999
18.0 KT AVERAGE
10.8 KT AVERAGE
10.8 KT - 85/79 RPM - 30% PITCH
18.0 KT - 113/113 RPM - 67/72% PITCH
Fig. D4
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
140
130
120
110
100
90
80
70
10
12.5
16
20
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
12500
16000
20000
25000
31500
40000
50000
63000
80000
100000

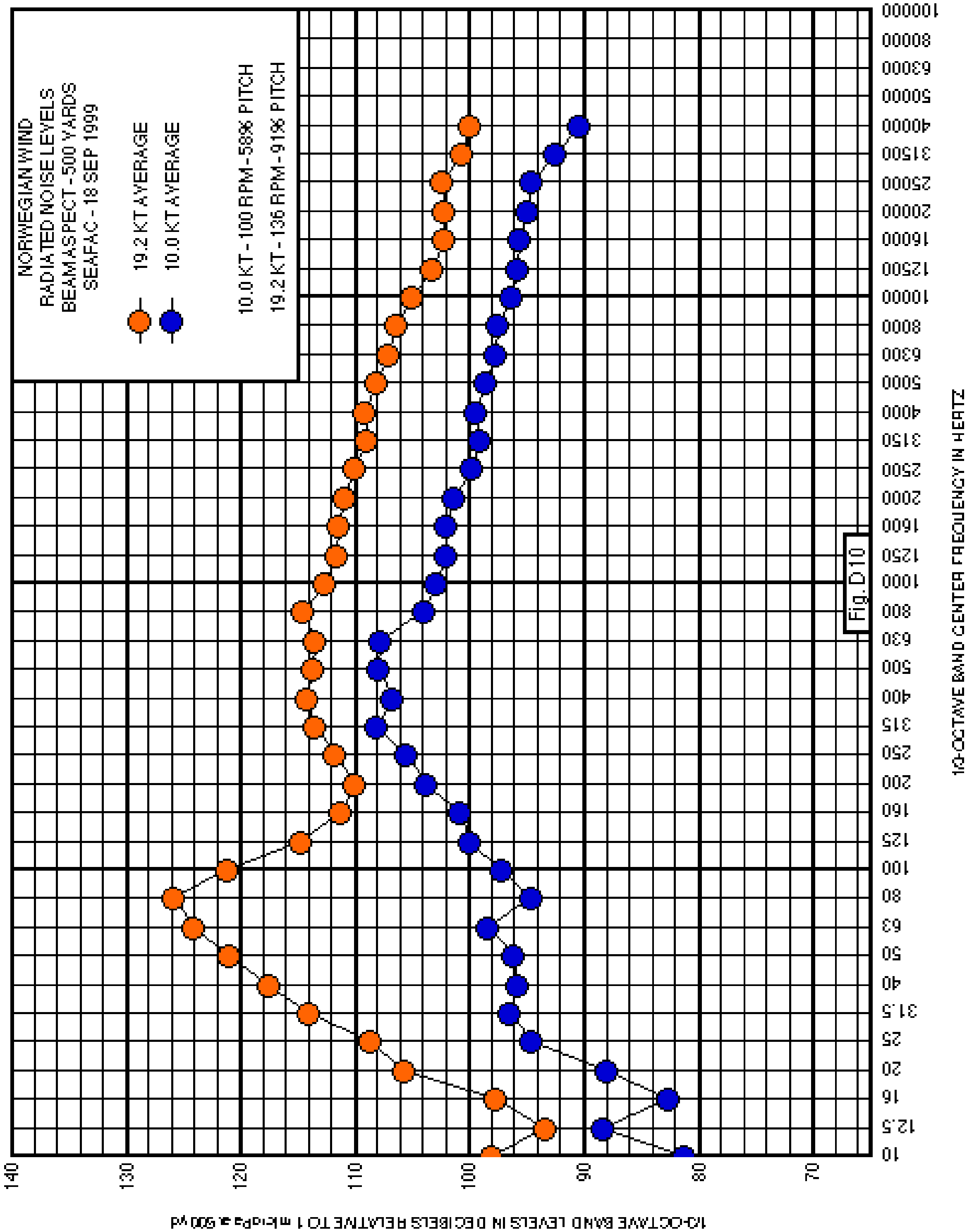

UNIVERSE EXPLORER
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 8 SEP 1999
10.0 KT AVERAGE
10.0 KT - 54 RPM
BROADBAND NOISE INCLUDING CAVITATION
MAIN REDUCTION GEARS
MAIN TURBINE ROTATION
TURBINE GENERATOR
Fig. D5
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ

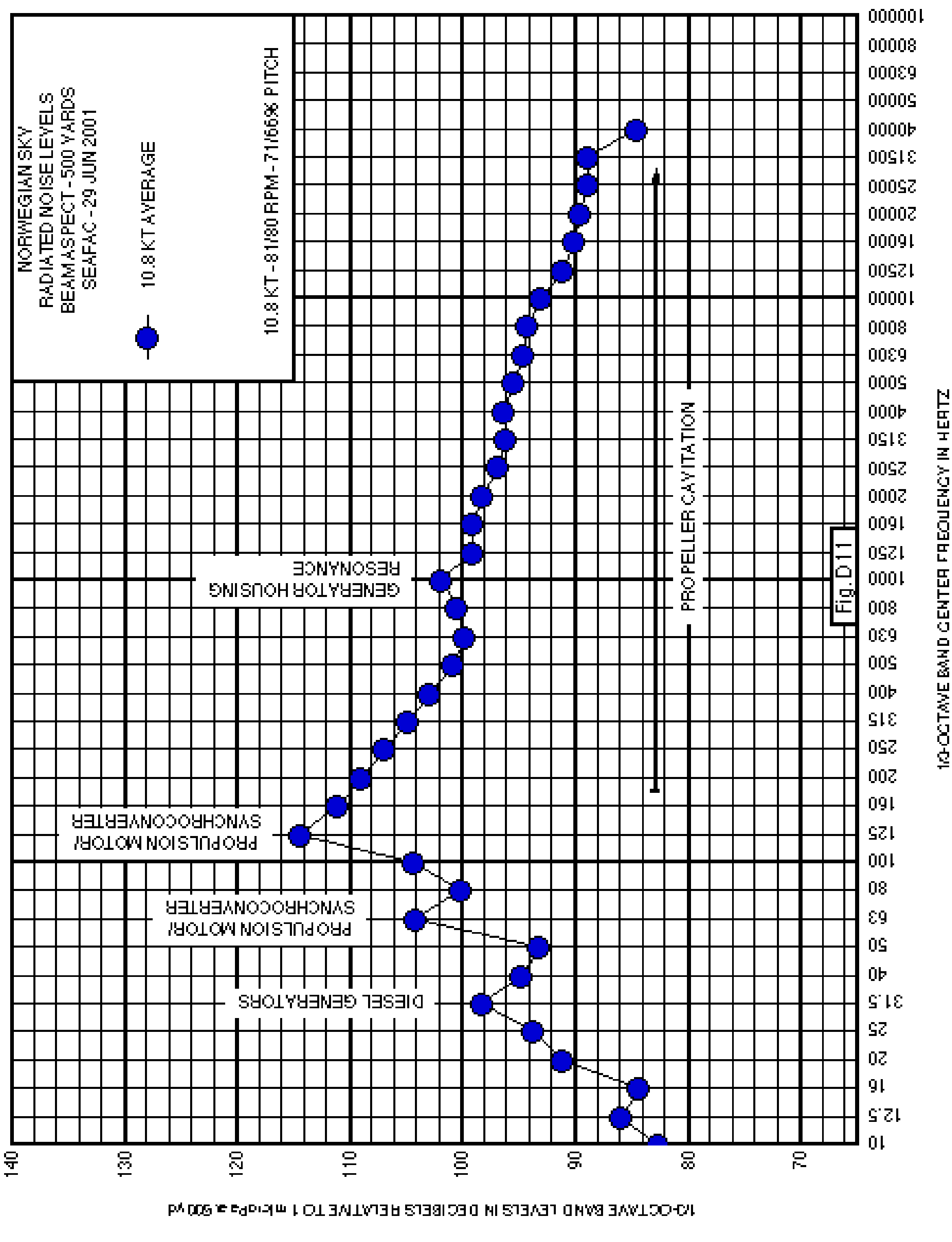

UNIVERSE EXPLORER
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 8 SEP 1999
15.5 KT AVERAGE
10.0 KT AVERAGE
10.0 KT - 54 RPM
15.5 KT - 84 RPM
Fig. D6
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd


DAWN PRINCESS
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 9 SEP 1999
10.0 KT AVERAGE
10.0 KT - 67 RPM
SYNCHROCONVERTER/
PROPULSION MOTOR
MACHINERY
Fig. D7
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd


DAWN PRINCESS
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 9 SEP 1999
5.6 KT AVERAGE
10.0 KT AVERAGE
5.6 KT - 40 RPM
10.0 KT - 67 RPM
Fig. D8
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd
140
130
120
110
100
90
80
70
10
12.5
16
20
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
12500
16000
20000
25000
31500
40000
50000
63000
80000
100000


NORWEGIAN WIND
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 18 SEP 1999
10.0 KT AVERAGE
10.0 KT - 100 RPM - 58% PITCH
REDUCTION GEAR
REDUCTION GEAR
A/C PLANT
CAVITATION
Fig. D9
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd


NORWEGIAN WIND
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 18 SEP 1999
19.2 KT AVERAGE
10.0 KT AVERAGE
10.0 KT - 100 RPM - 58% PITCH
19.2 KT - 136 RPM - 91% PITCH
Fig. D10
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
140
130
120
110
100
90
80
70
10
12.5
16
20
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
12500
16000
20000
25000
31500
40000
50000
63000
80000
100000


NORWEGIAN SKY
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 29 JUN 2001
10.8 KT AVERAGE
10.8 KT - 81/80 RPM - 71/66% PITCH
DIESEL GENERATORS
PROPULSION MOTOR/ SYNCHROCONVERTER
PROPULSION MOTOR/ SYNCHROCONVERTER
GENERATOR HOUSING RESONANCE
PROPELLER CAVITATION
Fig. D11
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd

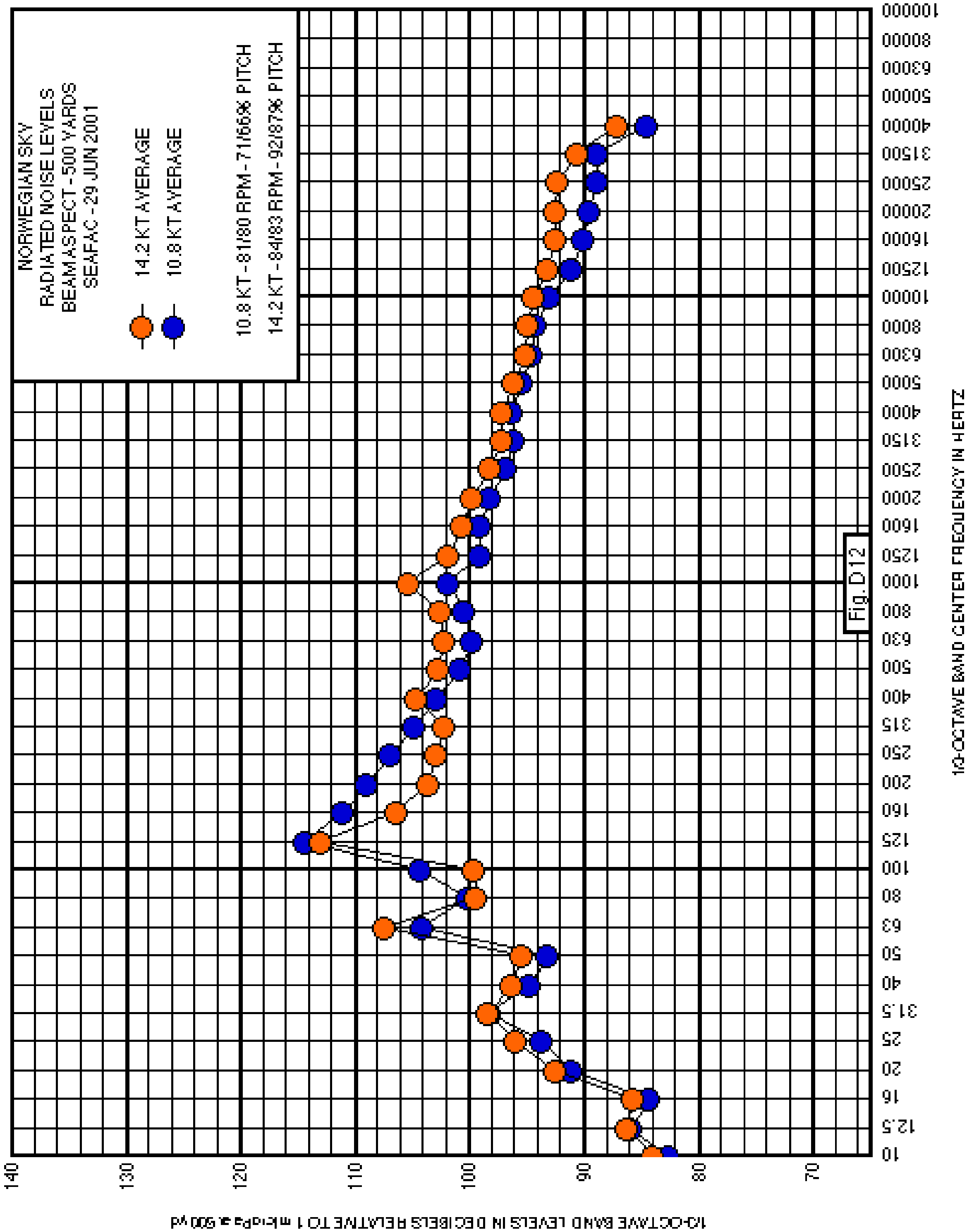
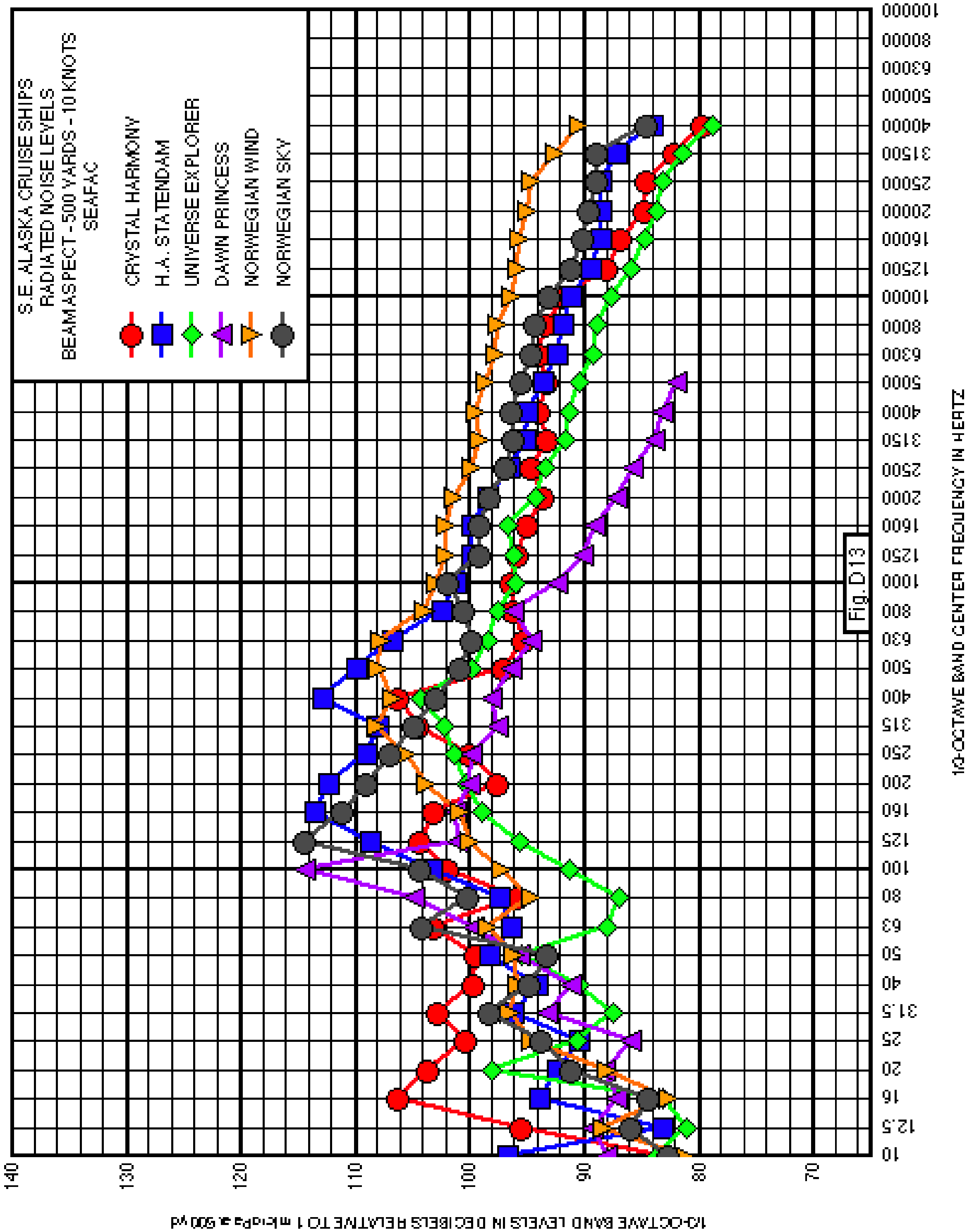
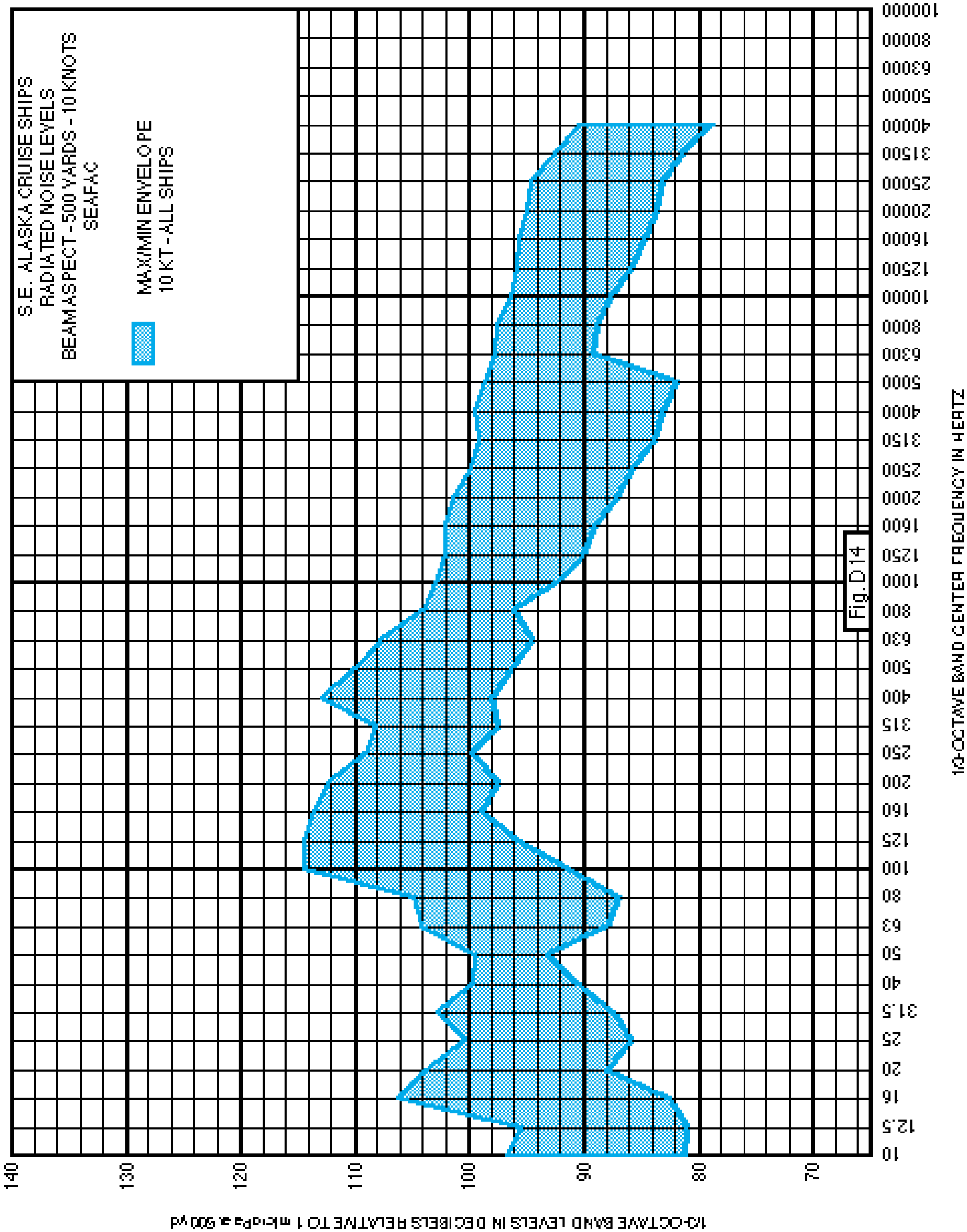
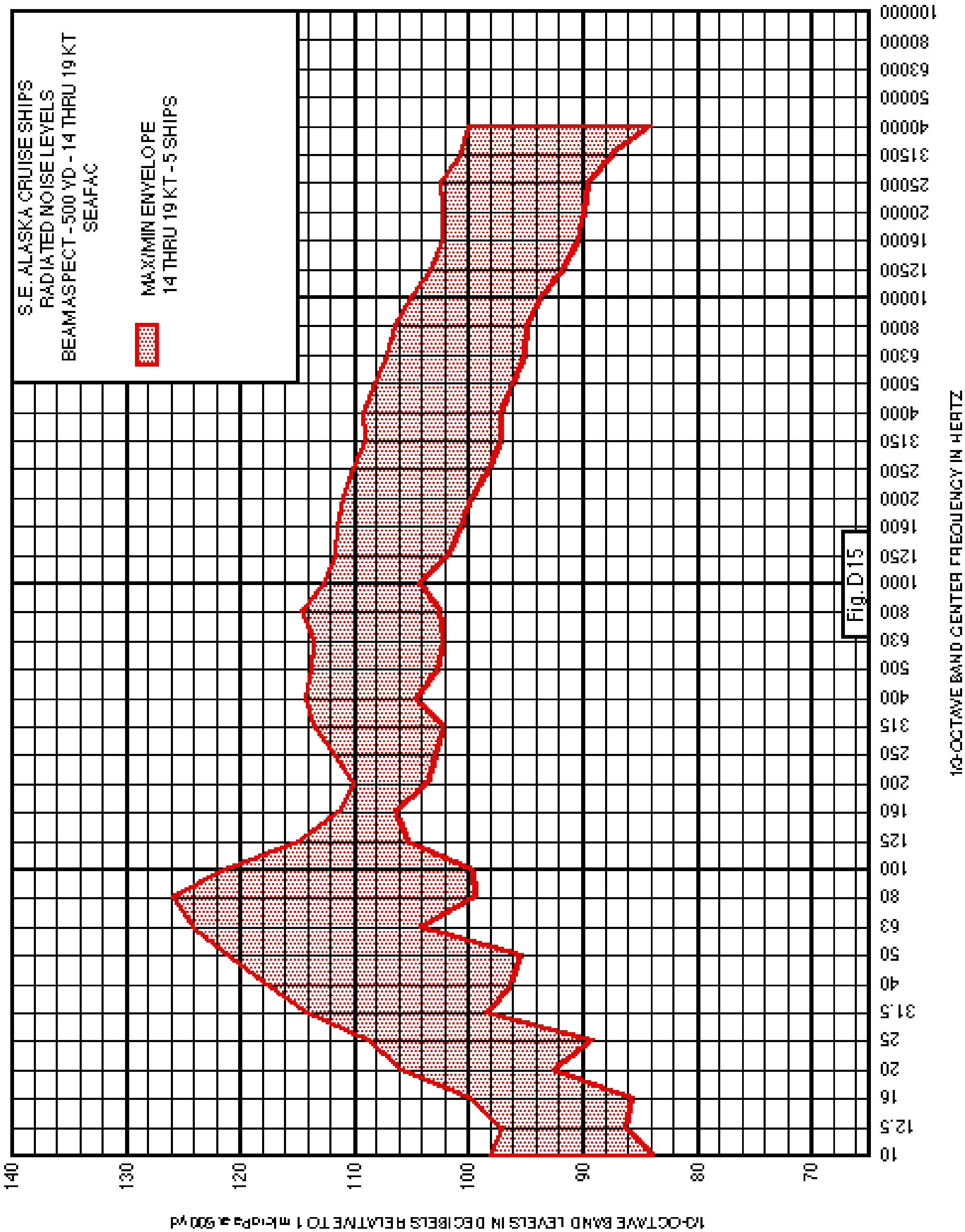

NORWEGIAN SKY
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS
SEAFAC - 29 JUN 2001
14.2 KT AVERAGE
10.8 KT AVERAGE
10.8 KT - 81/80 RPM - 71/66% PITCH
14.2 KT - 84/83 RPM - 92/87% PITCH
140
130
120
110
100
90
80
70
10
12.5
16
20
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
12500
16000
20000
25000
31500
40000
50000
63000
80000
100000
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd

Fig. D12


S.E. ALASKA CRUISE SHIPS
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS - 10 KNOTS
SEAFAC
CRYSTAL HARMONY
H.A. STATENDAM
UNIVERSE EXPLORER
DAWN PRINCESS
NORWEGIAN WIND
NORWEGIAN SKY
Fig. D13
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd


S.E. ALASKA CRUISE SHIPS
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YARDS - 10 KNOTS
SEAFAC
MAX/MIN ENVELOPE
10 KT - ALL SHIPS
Fig. D14
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd
10
12.5
16
20
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
12500
16000
20000
25000
31500
40000
50000
63000
80000
100000
140
130
120
110
100
90
80
70


S.E. ALASKA CRUISE SHIPS
RADIATED NOISE LEVELS
BEAM ASPECT - 500 YD - 14 THRU 19 KT
SEAFAC
MAX/MIN ENVELOPE
14 THRU 19 KT - 5 SHIPS
Fig. D15
1/3-OCTAVE BAND CENTER FREQUENCY IN HERTZ
1/3-OCTAVE BAND LEVELS IN DECIBELS RELATIVE TO 1 microPa at 500 yd
140
130
120
110
100
90
80
70
10
12.5
16
20
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
10000
12500
16000
20000
25000
31500
40000
50000
63000
80000
100000

Appendix E – Noise Levels for Cruise Ship with Azipod Propulsion

In March 1998, NSWC measured the underwater radiated noise levels of the Carnival Cruise Line ship Elation at speeds of 10 and 20 knots off of Grand Bahama Island*. These measurements were made at the request of the Defense Advanced Research Projects Agency. Elation was equipped with an azipod propulsion system consisting of two electric propulsion motors each located in a fully azimuthing external pod. This configuration was basically that of a diesel-electric ship, but with the propulsion motors located external to the hull, and with the ability to steer the motors about their vertical axis. The ship's propulsion system frequency converter was a 12 pulse cycloconverter with an output frequency ranging from 0 to 15 Hz. Other specifics of Elation are given in the table below.

Length	855 ft
Gross tonnage	70367
Engines	6 12-cylinder diesel
Propellers	4 blades, fixed pitch

Figure E1 shows one-third octave noise levels for 10 and 20 knots. Noise measurements were made at a nominal range of 300 yards, with hydrophones located at 250, 350, 550, 650 feet. The noise levels reported represent multi-hydrophone and multi-run averages. The water depth was 3000 feet. In the adjustment of the measured 300-yard levels to 1 yard, only spherical spreading was applied. No adjustments were made for multi-path propagation effects.

* These results are reported in NSWC report: "MS ELATION Acoustic Trial Results", CDNSWC-SIG-98/062-7120, April 1998.

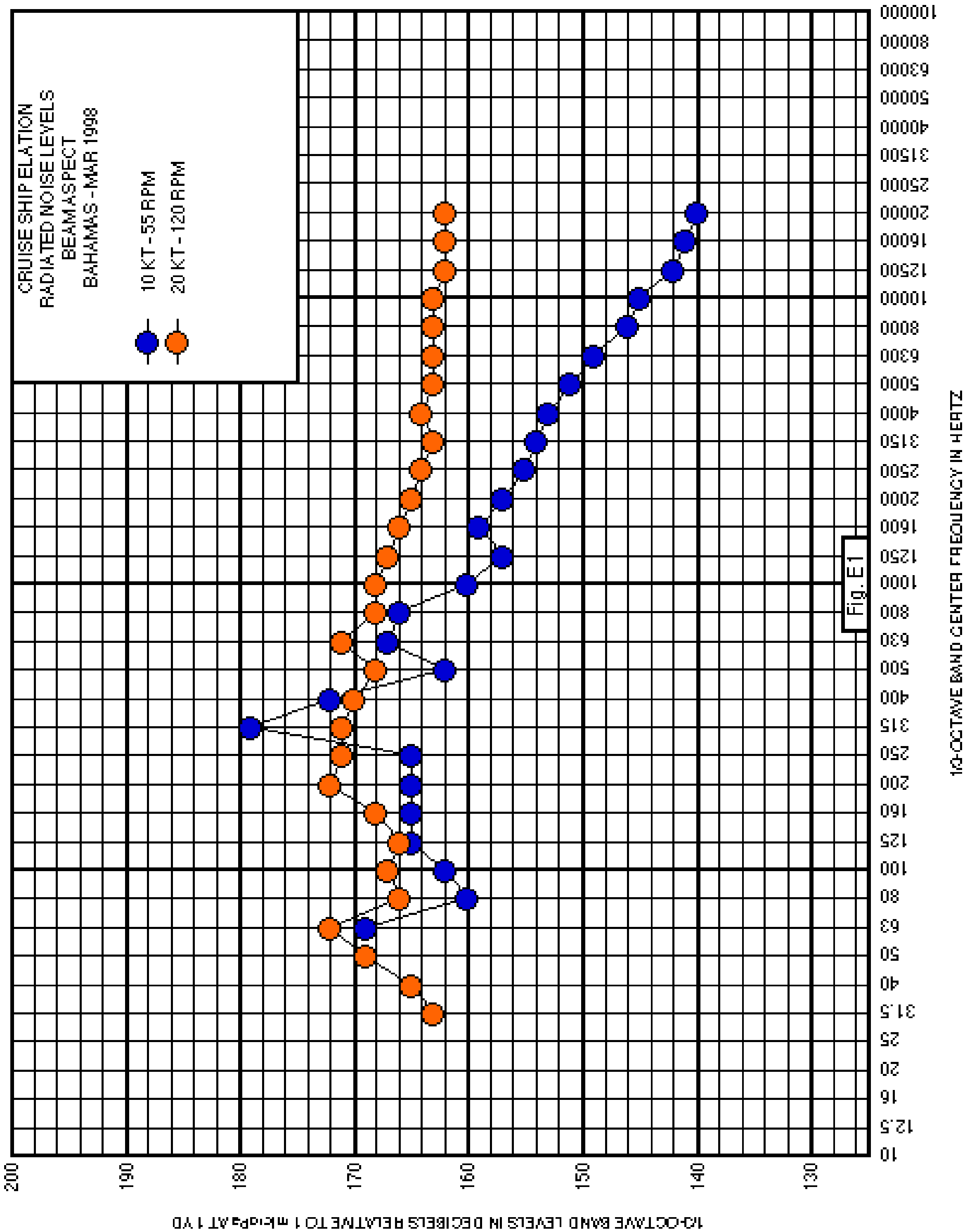


Fig. E1 Cruise Ship Elation 10 and 20 kt One-Third Octave Underwater Noise Levels

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