Rapport Report

Vurdering av støy i forbindelse med undervannseksplosjoner i Båtsfjord, april 2018

Akvaplan-niva AS Rapport: 60306 - 01

Forsidebilde – øverst: rigg som ble benyttet til arbeidet med utdyping av Båtsfjord Havn. Under: Torsk i torskehotellet. Foto: Akvaplan-niva

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Vurdering av støy i forbindelse med undervannseksplosjoner i Båtsfjord, april 2018

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Forord

Denne rapporten tar for seg resultater av støyovervåkning i forbindelse med undervannssprengning i Båtsfjord Havn i april 2018. Planlegging og gjennomføring av feltarbeid, samt rapportering er gjennomført av Akvaplan-niva og det franske firmaet Quiet-Oceans. Akvaplan-niva planla, tilrettela og var med på feltarbeidet, mens Quiet-Oceans var ansvarlige for måling i felt og analyse av støydataene i etterkant av feltarbeidet. Denne norskspråklige teksten er et kort sammendrag av den vedlagte engelskspråklige rapporten som Quiet-Oceans har utarbeidet.

Vi ønsker å takke mannskapet om bord på fartøyet *Havna*, for profesjonelt, fleksibelt og hyggelig samarbeid under feltarbeidet.

Akvaplan-niva og Quiet-Oceans takker Kystverket for oppdraget.

Akvaplan-niva takker Labora for godt samarbeid i forbindelse med undersøkelsene.

Tromsø, 24.08.2018

Guttorm N. Christensen

Sammendrag

Undervannsakustiske målinger ble gjennomført i forbindelse med undervannssprengninger i Båtsfjord Havn 24.-26. april 2018. Hensikten med sprengningene var å gjøre havneområdet dypere. Hensikten med målingene var å studere støynivået i fjorden under sprengningene og vurdere dette i lys av mulige konsekvenser for marint liv, inkludert torsk som holdes i et torskehotell omtrent 900 meter unna sprengningspunktet. I løpet av studieperioden ble fem sprengninger gjennomført, med ulike oppsett og ulike mengder sprengstoff (fra 56,7 til 529 kg dynamitt). Overvåking av støynivå foregikk ved at fire autonome akustiske opptakere ble plassert på forskjellige steder i fjorden, fra 900 meter til 13 100 meter fra sprengningspunktet. De akustiske systemene ble utformet for å kunne registrere både de svært lave nivåene av omgivende støy og de meget høye nivåene fra eksplosjonene. Måleresultatene viser at topp-til-toppverdiene for lydtrykket oppnådde maksimalt 216,8 dB ref 1µPa og et maksimalt lydeksponeringsnivå på 193 dB ref 1µPa²s i en avstand på 1100m fra sprengningsposisjonene. Topp-til-toppverdiene for lydtrykket viste svært liten variasjon (± 1,5 dB) for målinger med ulike eksplosivmengder, og dette kan forklares av bruken av mikroforsinkede ladninger. Bruken av slike mikroforsinkelser, samt at ladningene ble senket ned i havbunnen, bidro til redusert støynivå. Det ble observert betydelig bakgrunnsstøy i området, med verdier på 97-130 dB mesteparten av tiden, noe som er høyere enn i sammenliknbare områder. Bakgrunnsstøyen kan både være naturlig og menneskeskapt. Naturlig støy i sjøen vil blant annet kunne ha sin opprinnelse fra vind, bølger, strømninger, nedbør og marint liv. Menneskeskapt støy kan blandt annet stamme fra båter, industriaktivitet, osv. Normal ikke menneskeskapt støy i sjø vil derfor variere med vær, vind og andre forhold. Bølger kan støy med verdier over 20 dB, mens nedbør kan skape støy opp til 35 dB (Wilson et al. 1985, Nystuen and Farmer 1987). Typiske nivåer av bakgrunnsstøy i havet er 100 dB ref 1µPa² (havområder/offshore), 105 dB ref 1µPa² (kystområder) og 100-105 dB ref 1µPa² (store havneområder).

På den annen side blir lydnivånivåene som representerer en måling av energien til sprengningen, en økning på + 4dB. Den forventede økningen av energien var imidlertid + 10dB med hensyn til forskjellen mellom minimum og maksimal belastning av sprengstoff som ble brukt. Dermed er både fordelingen og konfigurasjon av ladningen så vel som bunnforholdene viktige parametere, og ladningens størrelse er i seg selv ikke nok til å forutsi lydnivået i havmiljøet.

Støy fra sprengning gjennomgikk en sterk demping og brytning som følge fjordens topografi. For eksempel var støynivået ved torskehotellet, som ligger delvis i le av en halvøy, langt lavere enn det den korte avstanden fra sprengningspunktet skulle tilsi (35 til 40 dB under det som måles langs en direkte bane i samme avstand fra sprengningspunktet). I tillegg ble det ved torskehotellet observert en betydelig større tidsmessig spredning av støy fra sprengningene enn på lokasjoner langs en direkte bane fra sprengningspunktet, som følge av både refleksjoner langs kysten og de ulike egenskapene til bunnsedimentene.

Lydtrykket målt ved inngangen til fjorden på 13 100 meter fra sprengningen var omtrent 35 dB sterkere enn bakgrunnsstøyen før og etter sprengningen. En grov numerisk beregning viser at lyden fra hver eksplosjon kan oppfattes opp til 96 til 400 km unna i henhold til nivået av omgivende støy. Med hensyn til toleranseterskelene for ulike arter (Popper, et al., 2014) og basert på de målte verdiene, nås grensen for fiskedødelighet ved 258-359 m. Til dags dato er tersklene for midlertidig skade eller endring av fiskens oppførsel som følge av støy (for eksempel i forbindelse med undervannseksplosjoner) ikke tilstrekkelig kjent, og dette kan derfor være gjenstand for komplementære studier.

For videre studier anbefales det også å fokusere på potensielle skjæringspunkt mellom støynivå, sprengningsintervallenes lengde, ladningenes plassering (antall meter ned i havbunnen) og effekten i form av hvor mye stein som brytes under sprengningene. Det bør også tas sikte på å utvikle en numerisk modell som kan brukes til å beregne spredning av støy fra sprengning, gitt ulike grunn- og topografiske forhold. En slik modell vil senere kunne brukes som ledd i miljørisikoanalyse under planlegging av spesifikke sprengningsarbeid under vann, for eksempel med tanke på å unngå støynivåer som er skadelige for sjøpattedyr eller andre marine dyr.

1 Innledning og målsetting

Kystverket fjernet stein- og fjellmasser under vann ved sprengning i Båtsfjord Havn i april 2018 for å øke seilingsdybden i dette området. Selve sprengningsarbeidet ble gjennomført av firmaet Aarsleff. Overvåkning av støynivået under vann ulike plasser i fjorden ble gjennomført av Akvaplan-niva og Quiet-Oceans 24.-26. april. Hensikten med målingene var å studere støynivået i fjorden under sprengningene og vurdere dette i lys av mulige konsekvenser for marint liv, inkludert torsk som holdes i et torskehotell omtrent 900 m unna sprengningspunktet.

Alle standard mål på lydnivå, inkludert topp-til-topp-verdier, 0-topp-verdier (amplitude) og lydtrykksverdier er registrert og presentert i rapporten. Hensikten med dette er å

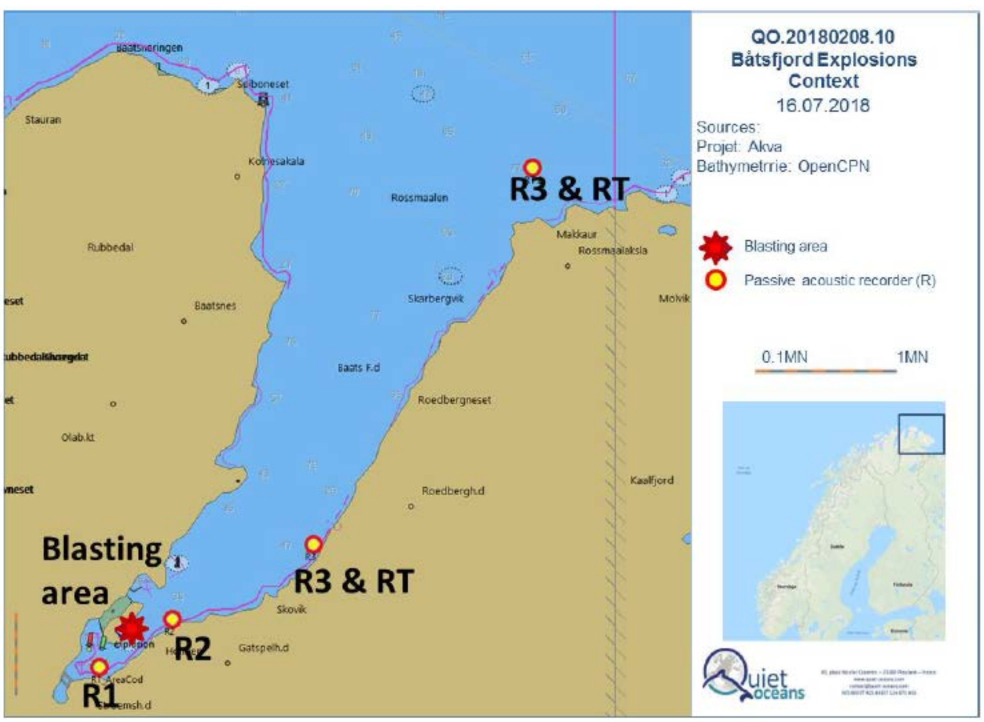
- studere hvordan støy forårsaket av undervannssprengning forplanter seg i en fjord som Båtsfjord
- studere bakgrunnsstøyen i fjorden
- skape en bedre forståelse av hvilke miljøkonsekvenser støy forårsaket av sprengning kan få.

2 Materiale og metode

2.1 Plassering av støymålere

Sprengningene ble gjennomført i havneområdet i den sørlige delen av Båtsfjord i perioden 24 – 26. april 2018 (Figur 1). Det ble brukt fire støymålere under feltarbeidet, og disse ble plassert på posisjonene R1, R2, R3 og RT. Ved R1, R2 og R3 ble det brukt støymålere som ble ankret fast i bunnen. Ved RT ble en støymåler hengt ut i vannsøylen fra båten Havna, for å kunne overvåke bakgrunnsstøy og støy fra sprengningene i sanntid. Posisjonen R1 lå like ved torskehotellet, omtrent 900 m sørvest for sprengningspunktet og delvis skjult bak halvøya Holmen. Hensikten med denne målestasjonen var å registrere hvilket støynivå torsken i torskehotellet ble eksponert for under sprengningene. Posisjonen R2 lå omtrent 1,1 km nordøst for sprengningspunktet, uten noen landmasser mellom stasjonen og sprengningspunktet. For den første sprengningen ble posisjonene R3 og RT lagt omtrent 4,4 km nordøst for sprengningspunktet. For de påfølgende sprengningene ble imidlertid R3 og RT flyttet ut til fjordmunningen, omtrent 13 km fra sprengningspunktet. Tidpunkter for utsett og opptak av de ulike støymålerne er oppgitt i Tabell 1.

En detaljert beskrivelse av de ulike støymålerne som ble brukt i studiet finnes i det engelskspråklige vedlegget.



Figur 1. Kart over Båtsfjord. Sprengningsområdet ("Blasting point") er vist som en rød stjerne i kartet, mens RT, R1, R2 og R3 viser hvor støymålere ble utplassert i perioden 24 – 26. april 2018.

Tabell 1. Tidspunkter for utsett og opptak av støymålere.

Point name	Recorder Name	Id Channel	Starting time UTC (HHMMSS)	Ending time UTC (HHMMSS)
Shot D2_S01 – 24 April 2018 08:34 UTC				
R1	ENR-017	01	070300	161700
R2	ENR-015	01 02	070300	161700
R3	ENR-018	01	070300	161700
RT	icl1738	01	080000	085400
Shot D2_S02 – 24 April 2018 12:34 UTC				
R1	ENR-017	01	121245	130000
R2	ENR-015	01 02	070300	161700
R3	ENR-018	01	070300	161700
RT	icl1738	01	121245	130000
Shot D2_S03 – 24 April 2018 15:44 UTC				
R1	ENR-017	01	151700	160000
R2	ENR-015	01 02	070300	161700
R3	ENR-018	01	070300	161700
RT	icl1738	01	151700	160000
Shot D3_S01 – 25 April 2018 19:33 UTC				
R1	ENR-017	01	191705	194300
R2	ENR-015	01 02	134200	194300
R3	ENR-018	01	134200	194300
RT	icl1738	01	191700	194300
Shot D4_S01 – 26 April 2018 14:56 UTC				
R1	ENR-017	01	142500	150500
R2	ENR-015	01 02	130500	153000
R3	ENR-018	01	130500	153000
RT	icl1738	01	142500	150500

2.2 Torskehotellet

Det ble montert en hydrofon i umiddelbar nærhet til torskehotellet (Figur 2) – Hydrofon R1 (Figur 1). I tillegg ble torsken i anlegget observert av en person, samt filmet, når de fem sprengningene i dette prosjektet ble gjennomført.

Figur 2. Torskehotellet i Båtsfjord. Foto: Akvaplan-niva.

2.3 Fartøy

Havnebåten til Båtsfjord havn "*Havna"* ble brukt til å sette ut og ta inn støymålere (Figur 3).

Figur 3. Fartøyet Havna, som ble brukt under feltarbeidet. Foto: Akvaplan-niva.

2.4 Sprengninger

Før hver enkelt sprengning ble utført, ble et varierende antall sprengningshull boret ned i fjellet der steinmasser skulle fjernes i henhold til et fastsatt romlig mønster: Et varierende antall dynamittladninger på 2,1 kg ble så senket ned i sprengningshullene slik at de til sammen utgjorde en *brønn*. Hver brønn må inneholde minst 8,4 kg dynamitt for at sprengningen skal ha noen effekt. For å unngå ekstremt høyt støynivå som følge av at alle ladningene ble sprengt samtidig, ble det lagt inn en forsinkelse mellom sprengningene av de ulike ladningene. Forsinkelse mellom sprengninger er standard prosedyre under undervannssprengning i regi av Kystverket. En forsinkelse på 25-50 millisekunder ble lagt inn mellom sprengningene av de ulike ladningene. Lengste mulig forsinkelse i denne sammenhengen er altså 50 millisekunder, men kortere forsinkelse enn dette ble anbefalt av Aarsleffs sprengningsansvalige. I tillegg til forsinkelse mellom sprengninger av de ulike ladningene i en brønn, bidrar også praksisen med å sprenge et antall meter ned i fjellet på havbunnen til at støynivået reduseres.

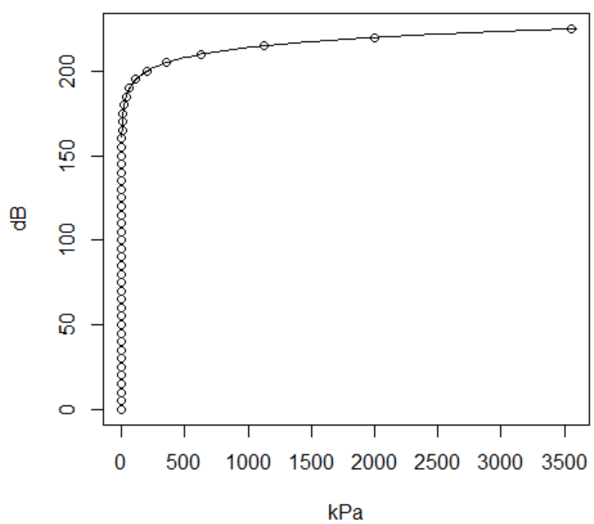
For den første sprengningen ble det totalt brukt 56,7 kg dynamitt, mens det for de påfølgende sprengningene ble brukt henholdsvis 75,6, 109,2, 529.2 og 144,9 kg dynamitt. For detaljert informasjon om sprengningene, se engelskspråklig vedlegg.

3 Resultater og diskusjoner

3.1 ANALYSE

3.1.1 Måleenhet

I denne rapporten er alle lydnivåer oppgitt i decibel (dB). Decibel er en måleenhet for akustisk trykk, som kvantifiserer oppfattet lydnivå og som følger en logaritmisk skala. Andre måleenheter for lydnivå eksisterer. En av disse er pascal/kilopascal.. Decibel er imidlertid gjeldende standard innen marin akustikk, siden denne enheten kan håndtere både høye og lave lydnivåer takket være den logaritmiske skalaen. Pascal kan ikke alene beskrive stor variasjon i lydnivå (både høye og lave nivåer), og dette er grunnen til at denne enheten er lite brukt innen marin akustikk. Sammenhengen mellom dB og kPa er oppgitt i Figur 4.

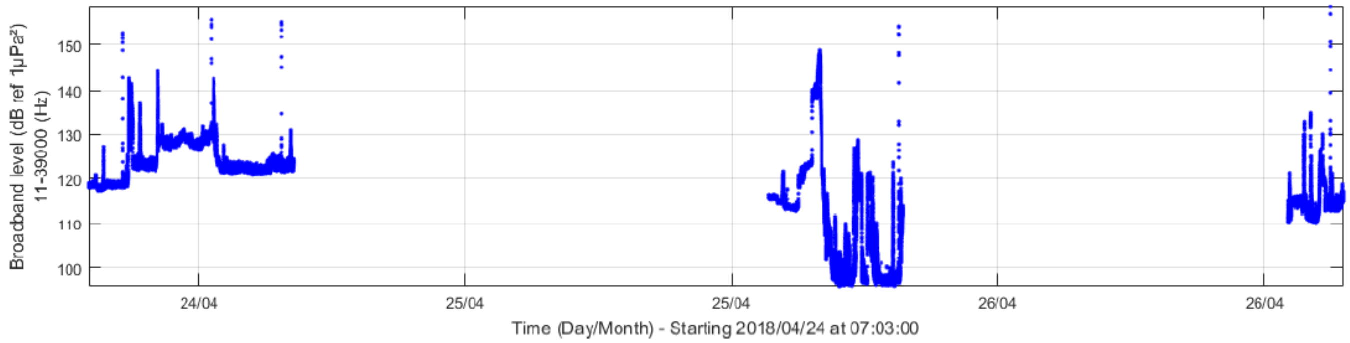


Figur 4. Forholdet mellom kilopascal (kPa) og decibel (dB).

3.1.2 Bakgrunnsstøy

Bakgrunnsstøyen i studieområdet ble overvåket i tre dager (Figur 5). Den første og den siste dagen ble det målt høye nivåer av bakgrunnsstøy (omtrent 110-140 dB), mens det ble målt noe lavere nivåer av bakgrunnsstøy den andre dagen (omtrent 90-130 dB). Lydtrykksnivået var sterkere enn 97 dB ref 1 μPa^2 95% av tiden og sterkere enn 130,4 dB ref 1 μPa^2 5% av tiden. Medianverdien for bakgrunnsstøy (lydtrykksnivå) i løpet av de tre dagene var 119,7 dB ref 1μPa^2.

I studieperioden var bakgrunnsstøyen i Båtsfjord omtrent 10 dB høyere enn i sammenliknbare havneområder. Dette kan delvis forklares med typen sjøbunne i Båtsfjord, som i relativt stor grad reflekterer lyd. I tillegg er det stor båttrafikk (hovedsakelig fiskefartøy) i fjorden. Dette understøttes av Figur 9 i den engelskspråklige delen av denne rapporten, som viser at Båtsfjord er en av de travleste havnene i Nord-Norge. Typiske nivåer av bakgrunnsstøy i havet er 100 dB ref 1µPa² (havområder/offshore), 105 dB ref 1µPa² (kystområder) og 100-105 dB ref 1µPa² (store havneområder).



Figur 5. Bakgrunnsstøy i Båtsfjord i studieperioden.

3.1.3 Dyreliv i studieområdet

Undersøkelser av marint biologisk mangfold i området er ikke en del av dette studiet.

I dette studiet ble det ikke aktivt søkt etter sjøpattedyr ved hjelp av hydrofon. Imidlertid forekommer mange arter av sjøpattedyr i Nord-Norge (se liste over aktuelle arter i det engelskspråklige vedlegget), og både nise (*Phocoena phocoena*; Figur 6) og sel (steinkobbe, *Phoca vitulina*, Figur 7) ble observert i studieområdet i løpet av studieperioden.

Figur 6. Bilde av nise, tatt ved fjordmunningen i Båtsfjord 24 april 2018.

Figur 7. Steinkobbe. Foto: Akvaplan-niva

3.2 Sprengningsrelatert støy

Støynivå ved de ulike målestasjonene i Båtsfjord under sprengninger 24.-26. april 2018 er oppgitt i Tabell 2. Støynivået var svært ulikt ved de to målestasjonene som lå nærmest sprengningspunktet (R1 og R2). Ved R2, som ble direkte eksponert for støy forårsaket av sprengningene, ble støynivåer opp mot 215 dB ref 1µPa (topp-til-toppverdi) målt. Ved R1 (ved torskehotellet), som lå delvis skjult bak landmasser, var støynivået betydelig lavere (177.3-191.3 dB ref 1µPa). Støynivået ved torskehotellet var sammenlignbart med støynivået ved de ytterste stasjonene som lå over 13 km i rett linje fra sprengningspunktet.

På en gitt målestasjon medførte sprengninger med ulike mengder sprengstoff (56-529 kg) kun en marginal forskjell i støynivå under vann. Dette tilskrives de korte forsinkelsene mellom ladningene, som bidro til at støytoppen ble spredd over et lengre tidsrom.

Hvor langt unna man kan registrere en sprengning avhenger av hvor mye bakgrunnsstøy det er. Basert på de målte verdiene av bakgrunnsstøy og sprengningsrelatert støy ved R2 og R3 anslås det at sprengningene som ble gjennomført i Båtsfjord kunne blitt registrert under vann inntil 96-400 km fra sprengningspunktet.

Tabell 2. Støynivå på ulike posisjoner i Båtsfjord under undervannssprengning i havneområdet 24.-26. april.

Shot	Date	Blasting time UTC	Recorder	Location	Distance from blasting point (m)	SPL pk-pk (dB ref 1µPa) Unweighted	SPL 0-pk (dB ref 1µPa) Unweighted	SPL rms (dB ref 1µPa) Unweighted	SEL (dB ref 1µPa^{2}s) Unweighted
D2_S01	24/04/2018	08:34:00	ENR-018	R1	900	177.3	171.9	154.1	153.6
			ENR-015	R2	1100	214.3	208.6	192.2	188.2
			ENR-017	R3	4500	*NA*	*NA*	*NA*	*NA*
			icl1738	RT	4500	*NA*	*NA*	*NA*	*NA*
D2_S02	24/04/2018	12:34:00	ENR-018	R1	900	181.6	176.4	158.8	157.0
			ENR-015	R2	1100	216.8	212.3	193.7	189.8
			ENR-017	R3	13100	166.1	161.6	135.0	134.0
			icl1738	RT	13100	172.0	167.7	151.0	146.0
D2_S03	24/04/2018	15:44:50	ENR-018	R1	900	179.2	175.4	157.8	156.3
			ENR-015	R2	1100	214.5	210.0	192.6	188.7
			ENR-017	R3	13100	172.6	166.9	155.8	147.7
			icl1738	RT	13100	167.3	161.5	146.3	145.9
D3_S01	25/04/2018	19:32:00	ENR-018	R1	900	176.0	171.0	154.9	154.8
			ENR-015	R2	1100	215.0	210.8	196.1	193.0
			ENR-017	R3	13100	170.8	165.9	154.7	152.1
			icl1738	RT	13100	174.6	169.2	158.6	155.6
D4_S01	26/04/2018	14:56:00	ENR-018	R1	900	191.3	188.3	166.3	162.8
			ENR-015	R2	1100	*NA*	*NA*	*NA*	*NA*
			ENR-017	R3	13100	171.4	166.4	155.5	149.9
			icl1738	RT	13100	171.8	166.7	155.7	150.9

3.3 Støyrelatert risiko for fisk

Popper et al. (2014) definerte terskelverdier for hvilke støynivåer som kan medføre dødelighet hos fisk. Basert på kunnskap om hvilke fiskearter det er i området vil man derfor kunne definere risikoområder når man planlegger sprengningsarbeid under vann. Analyser av støydata innhentet i løpet av dette feltarbeidet indikerer at de aktuelle sprengningene medførte dødelige støynivåer på inntil 258-359 meters avstand fra sprengningspunktet, avhengig av terskelverdien (det vil hvilken fiskeart som blir eksponer). Det er på bakgrunn av målingene derfor usannsynlig at torsk i torskehotellet ble utsatt for dødelige støynivåer under sprengningene i studieperioden.

Torsken i torskehotellet (Figur 8) ble observert under de fem sprengningene som ble gjennomført i forbindelse med dette studiet. Det ble ikke påvist reaksjoner hos torsken under detonering av eksplosivene. Det ble observert torsk i torskehotellet med uvanlig adferd og svømmende på siden eller opp-ned, men dette kan ikke settes i sammenheng med undervannssprengningene. Denne adferden skyldes trolig håndtering av fisken i forbindelse med fanging.

Figur 8. Torsk i torskehotellet i Båtsfjord. Foto: Akvaplan-niva.

3.4 ANBEFALINGER

Basert på erfaringer fra dette prosjektet ønsker vi å fremme følgende anbefaling for fremtidig arbeid med undervannssprengning:

- Forsinkelse mellom sprengning av ulike ladninger i samme brønn, samt å utføre sprengningene et antall meter ned i havbunnen, bidrar trolig sterkt til å redusere støynivået og skåne havmiljøet. Videre studier bør fokusere på potensielle skjæringspunkt mellom støynivå, sprengningsintervallenes lengde, ladningenes plassering (antall meter ned i havbunnen) og effekten i form av hvor mye stein som brytes under sprengningene.

- Videre studier bør også ta sikte på å utvikle en modell som kan brukes til å beregne spredning av støy fra sprengning, gitt ulike grunn- og topografiske forhold. En slik modell vil kunne brukes som ledd i miljørisikoanalysen under planlegging av spesifikke sprengningsarbeid under vann, for eksempel med tanke på å unngå støynivåer som er skadelige for sjøpattedyr eller andre marine dyr.

- Unngå sprengning dersom det finnes fiskehotell eller oppdrettsanlegg innenfor risikoområdet, eventuelt flytte slike anlegg under sprengningene.

- I områder med kjente forekomster av sensitive marine dyr, for eksempel sjøpattedyr, bør området rundt sprengningspunktet overvåkes med passiv akustikk minst den siste halvtimen før sprengning tar til, for å sikre at det ikke er sjøpattedyr i nærheten under sprengningene. Videre bør området rundt sprengningspunktet overvåkes med passiv akustikk den påfølgende halvtimen etter sprengning for å kunne påvise eventuell unormal aktivitet i det marine miljøet.

4 Litteratur

Popper, A.N., Hawkins, A.D., Fay, R.R. and Tavolga, W.N. 2014. ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI (pp.33-51).

Nystuen, J. A. and D. M. Farmer (1987). The influence of wind on the underwater sound generated by light rain. J Acoust Soc Am **82**: 270-274.

Wilson, O. B. J., S. N. Wolf and F. Ingenito (1985). Measurements of acoustic ambient noise in shallow water due to breaking surf. J Acoust Soc Am **78**(1): 190-195.

5 Vedlegg

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Underwater explosions assessment in Båtsfjord

Technical Report

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Glossary

This section defines the technical terms used in the report.

Ambient noise

The part of the total noise background observed with a non-directional hydrophone, which is not due to the hydrophone and its mooring (self-noise), or to some identifiable localized source of noise.

Environmental background noise not of direct interest during a measurement or observation; may be from sources near or far, distributed and discrete, but excludes sounds produced by measurement equipment, such as cable flutter.

For a specified signal, all sound in the absence of that signal except that resulting from the deployment, operation or recovery of the recording equipment and its associated platform.

Ambient noise is the sum of natural noise and maritime traffic noise (to differentiate it from ambient natural noise produced by environmental conditions)

Bandwidth

The frequency range within a recording system is sensitive. The frequency range (in Hertz - Hz) is obtained by subtracting the lower from the upper cut-off frequency.

BDT

Behaviour Disturbance Threshold

Broadband level

The sound pressure level obtained over a wide frequency range with defined bandwidth.

Centre frequency

The geometric mean of the lower and upper cut-off frequencies. Please note that the intensities should be averaged before converted into decibels.

Continuous sound

Imprecise term meaning a sound for which the mean square sound pressure is approximately independent of averaging time.

A sound with no clear definable beginning or end, with no bandwidth restrictions, and a large time bandwidth produced when the frequency range is broadband. Continuous sounds have finite power, but may have infinite or at least undefined energy.

Decibel (dB)

Decibel (dB) is a measure of the level of acoustic pressure. It quantifies the perception of sound level. It is a logarithmic scale that describes a multiple of a reference value. As the sound volume doubles, the value in decibel increases by 3 dB. In marine acoustics, the reference level of decibel is 1 µPa (micro Pascal).

Using decibel is the standard in marine acoustics. The reason is that it can handle both with low and high values thanks to its logarithmic scale. The Pascal unit alone cannot easily represent the variation of sound levels from low to high and is therefore not used in marine acoustics.

Footprint (Ocean Noise Footprint)

The ocean noise footprint is the representation of noise levels due to maritime activities that affect a portion of sea. It includes the description of the noise sources, their distribution, and the propagation of sound in the ocean environment. It can be represented as a noise map [1] [2] .

ICI

ICI (**I**nter-**C**lick **I**nterval) refers to the time interval (in millisecond) between two consecutive clicks (impulsive signals) usually emitted by marine mammals.

LAT

Lowest Astronomical Tide, used as reference on bathymetric charts.

Natural ambient noise

Ambient noise in the absence of any contribution from anthropogenic sources.

Noise

Noise is in direct contrast to signals, but is always depending on receiver and context. What one receiver considers noise may be a signal to another. Even for the same receiver the exact same sound can be either signal or noise, depending on context.

"Noise" can be used in a more restrictive meaning where adverse effects of sound are specifically described or when referring to specific technical distinctions such as "masking noise" or "ambient noise".

Percentile level

A percentile corresponds to the proportion of time and space for which the noise exceeds a given level. This concept is widespread even in everyday life. For example, the average income of the top 10% of income earners, or the "income threshold corresponding to the 90th or to the 95th percentile", i.e. the income earned by the poorest individual among the top 10% or top 5% richest individuals. Meanwhile, the 50th percentile corresponds to the median salary. For underwater noise, the percentile, or exceedance level, is meant to describe the noise level occurring at least half of the time.

In the context of underwater noise, it is defined as the level L_N that is exceeded N percent of the time interval considered. For example, L_1 is the level that is exceeded 1% of the time.

The L_1 is a measure for the maximum level. It is a more robust estimate than taking just the maximum observed level, since the latter may be an outlier caused by a single event, such as rattling of the anchoring system or other types of self-noise. Accordingly, L_{99} and L_{95} are used to describe the minimum level. L_{50} is the median level.

PTS

Permanent Threshold Shift

Reference pressure

1 µPa in underwater acoustics.

Sound

The term "sound" is used to refer to the acoustic energy radiated from a vibrating object, with no particular reference for its function or potential effect. "Sounds" include both meaningful signals and "noise" (defined below), which may have either no particular impact or a range of adverse effects.

Sound pressure

Instantaneous pressure at time t.

p(t) in [Pa].

Sound Exposure

The integral of the square of the sound pressure over a stated time interval or event.

E in [µPa²s], $E = \int_0^T p(t)^2 \, dt$, with T being the time period of the event of interest.

Sound Pressure Level

SPL in [dB re 1 µPa]

$$SPL = 10 \cdot log_{10} \frac{{}^{1}/_{T} \int_{0}^{T} p(t)^2 dt}{p_0^2} = 10 \cdot log_{10} \left(\frac{p_{rms}}{p_0}\right)^2 = 20 \cdot log_{10} \left(\frac{p_{rms}}{p_0}\right)$$

With T = integration time.

Sound Exposure Level

SEL in [dB re 1 µPa²s]

$$SEL = 10 \cdot log_{10} \left(\frac{E}{p_0^2\, T_0}\right) = SPL + 10 log_{10}(T)$$

When the reference time T_0 is set to 1 s, the notation is 1sec-SEL or SEL.

When the T_0 is the time period of the event of interest in seconds, the notation is Tsec-SEL.

Third-octave frequency band

A frequency band with one third of an octave bandwidth. One octave is a doubling of frequency, whereas one third of an octave is a frequency ratio of $2^{1/3}$ (≈ 1.26) between the highest and the lowest. [3] [4] .

TTS

Temporary Threshold Shift

T_{90}

For pulsed sound (e.g. airguns, pile driving, explosive), the pulse length T90% is taken as the time between the 5% and the 95% points on the cumulative energy curve. SPLrms90% is computed by integrating $p(t)^2$ from T5% to T95%

Reference documents

[1] QO.20180208.01.PAQ.001.01A.AKVA.Explosive.Quality Management Plan.pdf

[2] QO.20180208.10.MEM.005.03A.AKVA.Protocol.pdf

[3] QO.20180208.10.MEM.007.01A.AKVA.Follow_up_meeting_20180524.pptx

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Executive summary

Underwater acoustic measurements were carried out in the Båtsfjord fjord from 24 to 26 April 2018 during dynamite-type explosive blasting operations as part of a future expansion of the mooring area.

During this period, five buried explosive blasting operations of different loads (from 56.7 to 529 kg of dynamite) were made in different configurations. Special attention was given to the effects of this activity on fish from the fish farm located at the end of the fjord at a distance of 900m.

Four autonomous acoustic recorders were deployed at various locations in the fjord, monitoring sound at various distances ranging from 900m to 13,100m. The acoustic systems deployed were designed to be able to record both the very low levels of ambient noise and the very high levels from the explosions.

The measurement results show that the peak-to-peak values of the Sound Pressure reached a maximum of 216.8 dB ref 1µPa and a maximum Sound Exposure Level of 193 dB ref 1µPa²s at a distance of 1,100m from the blasting positions. The peak-to-peak values of the Sound Pressure have shown very small variations (± 1.5dB) for all measurements, although explosive loads ranged from 56.7 to 529 kg of dynamite. This can be explained by the repartition of the total charge in groups, which blasting shots are separated by micro-delays.

On the other hand, the Sound Exposure Level, which represents a measurement of the energy of the blasting, undergoes an increase of +4dB. The expected increase of energy however was + 10dB taking into account the difference between the minimum and the maximum load of explosives used. This difference should be explained by the local bathymetrical and geographical configuration, the way explosive charges have been disposed, the charge unit and the duration of micro-delays between blasts.

Thus, the bathymetric context, the distribution and the configuration of the unitary charges are significant parameters and the solely value of the total charge of the explosion is not enough to predict the sound levels in the marine environment.

The sounds perceived at the location of the fish farm (900m away) undergo a strong attenuation and refraction by the topography of the fjord. The perceived levels in the frequency band of sensitivity of fish and measured at the location of the fish farm are 35 to 40 dB below those measured along a direct path at the same distance. The temporal signal at the fish farm has a significantly larger temporal spreading because of the multiple reflections along the coast line and in the different features of the bottom sediment. Sound Pressure Level measured at the entrance of the fjord at 13,100m away from the blasting showed a significant exceedance of sound in the order of 35 dB compared to the measured ambient noise levels before and after the blasting. A rough extrapolation using a geometrical law calculation shows that the sound from each explosion can be perceived 96 up to 400 km away according to the level of ambient noise.

With respect to the tolerance thresholds proposed by (Popper, et al., 2014) and based on the measured data, the distance to which the fish mortality threshold has been reached ranges from 258 to 359m. To date, the thresholds for a temporary damage or a modification of the behaviour of the fish in the presence of explosive sounds are not sufficiently known, and could therefore be the topic for complementary studies.

Chapter I. Context and objectives

I.1. Context of the study

Kystverket requested to remove bedrocks in Båtsfjord to increase sailing depth. Explosives have been used for this purpose. Akvaplan-niva has requested the expertise of Quiet-Oceans to perform measurements and associated analysis of underwater noise and pressure related to a series of representative blasting at different distances form the explosion point.

I.2. Objectives and Scope of Work

The work done in the framework of this project has been divided in three phases:

- drafting the monitoring program and detailed protocol, including the selection of the most suitable equipment and positions that enable to gather pertinent data, and an operational protocol to insure that measurement is made right from the first time as explosions would not be made again;
- implementing measurements in April 2018 in cooperation with Kystverket and Aarsleff;
- analysing underwater acoustic sounds produced by blasting operations.

I.3. Definition of the metrics used in the report

The metrics that will be calculated from the received signal for all available data during blasting are:

1- Peak-to-peak Sound Pressure Levels (broadband);
2- 0-to-peak Sound Pressure Levels (broadband);
3- 1-second Sound Exposure Levels;
4- RMS Sound Pressure Levels.

I.3.1. Peak-to-peak levels

The peak sound pressure is the maximum sound pressure during a stated time interval. A peak sound pressure may arise from a positive or negative sound pressure. The unit is the pascal (Pa). This quantity is typically useful as a metric for a pulsed waveform, such as airgun sources.

The calculation of peak-to-peak pressure levels used in this study is defined as follows:

$$\mathrm{SPL}_{pp} = 20log_{10}(((\max(p(t)) - \min(p(t)))/po)$$

over a short period (typically 0.5 s) in dB ref. 1µPa, and where *p(t)* is a signal in µPa.

p_0= 1µPa is the reference sound pressure.

I.3.1. 0-peak levels

The 0-peak sound pressure is the maximum sound pressure during a stated time interval. A 0-peak sound pressure may arise from a positive or negative sound pressure. The unit is the pascal (Pa). This quantity is typically useful as a metric for a pulsed waveform, such as impulsive sources.

The calculation of 0-peak pressure levels used in this study is defined as follows:

$$\mathrm{SPL}_{pp} = 20log_{10}((\max(|(p(t)|))/po)$$

over a short period (typically 0.5 s) in dB ref. 1µPa, and where *p(t)* is a signal in µPa.

p_0= 1µPa is the reference sound pressure.

I.3.2. 1-second Sound Exposure Levels

The sound exposure level is the integral of the square of the sound pressure over a stated time interval or event (such as an acoustic pulse) between a starting time t_1 and an end time t_2. The time difference between t_1 and t_2 is equal to 1 second. Sound Exposure Levels are expressed in dB re 1µPa²s. Sound Exposure levels are expressed as broadband levels, third-octave levels according to [4] , 1/10th octave levels. The calculation of 1s-SEL (or SEL) levels used in this study is defined as follows:

$$\text{SEL}= 10log_{10}(\int_0^T \text{p(t)}^2 / \, p_o^2 \, \text{dt})$$

Expressed in dB ref1µPa²s where T is the time integration equal to 1 second.

p_0= 1µPa is the reference sound pressure.

I.3.3. Sound Pressure Levels

The root mean square sound pressure is the square root of the mean square pressure of the received signal, where the mean square pressure is the time integral of squared sound pressure over a specified time interval T divided by the duration of the same time interval. The RMS sound pressure is calculated by first squaring the values of sound pressure, averaging over the specified time interval, and then taking the square root:

$$\text{SPL}_{\text{rms}}=20log_{10}(\sqrt{\frac{1}{T}\int_0^T p(t)^2 / \, p_o^2 \, dt})$$

The root mean square sound pressure is defined as broadband levels, third-octave levels according to [4] , 1/10th octave levels, and is expressed in dB ref1µPa².

p_0= 1µPa is the reference sound pressure.

I.3.4. Source level

Source Levels are equal to twenty times the decimal logarithm of the product of the far-field sound pressure and the distance from the source in a specified direction. Its unit is the dB re 1 µPa·@1m (understood as dB re 1 µPa referred to 1m).

The source level is a measure of the acoustic output of a source, and may be considered as a characteristic property of the source itself, independent of the propagation path from source to receiver position.

The Source Levels are defined as broadband levels or third-octave levels according to [4] , 1/10th octave levels.

Chapter II. Description of the dataset available

In order to evaluate underwater noise products by shallow water blasting operations, four underwater acoustic recorders were deployed at different locations in Båtsfjord bay during three days (24 to 26 April 2018). During this period, five explosive operations were conducted with different charges, different micro-delays, and different geographical configurations.

II.1. Acoustic monitoring strategy

The measurement strategy is illustrated in Figure 1. It consists in making measurements with instrumentation designed for measuring high levels and lower levels (for ambient noise) at several distances in order to:

- assess the propagation of the acoustic wave;
- assess ambient noise levels;
- reduce experimental risk.

Distances and positions need to be defined according to:

- - the charges used for the explosions;
- - how the charges are designed (confined or unconfined);

in order to avoid the risk of saturation of the acoustic instruments.

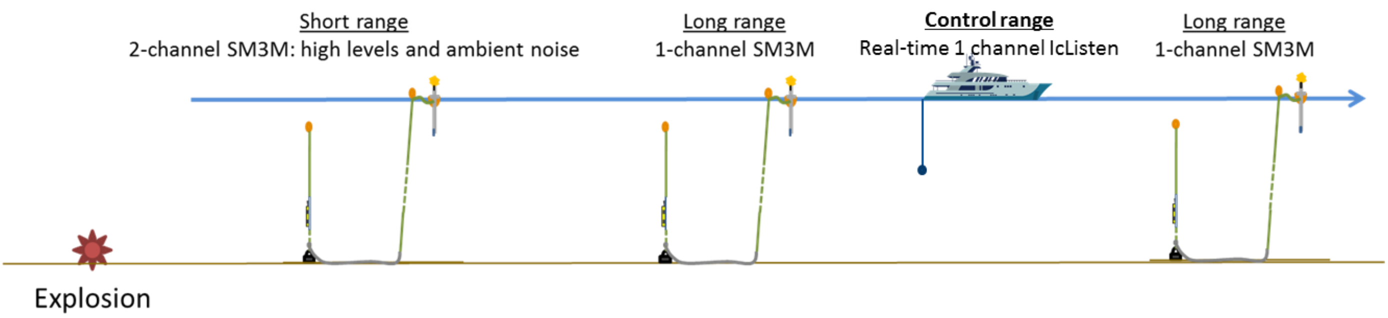


Figure 1: Measurement strategy

II.2. Acoustic deployments

From 24 to 26 April 2018, a set of blasting operations were conducted in the south part of the harbour. During these operations, four acoustic recorders were deployed at fixed positions in order to analyse the physical underwater noise produced by this anthropogenic activity.

The setup of the monitoring is illustrated in Figure 2, and exact coordinates are given in Table 1.

- A first recorder is placed at R1 in the vicinity of the so-called “cod hotel” which is a fish farm for Cod. The objective of this observation point is to evaluate the fish’s exposure to underwater sounds produced by the blasting operations. R1 is not located in the direct acoustic path from the blasting positions but reflections along the coastline is likely to occur all around the fjord;
- A second recorder is placed at R2 and is devoted to measurement of the direct acoustic path at the shortest distance possible. The settings of this recorder are such that it can measure high levels;
- A third recorder is placed at R3 and RT initially located at 4,500m from the blasting area, but moved to a larger distance of 13,100 m in the direct path in order to capture both the ambient noise levels and the blasting signature without clipping.

Figure 2: Context of the experiment.

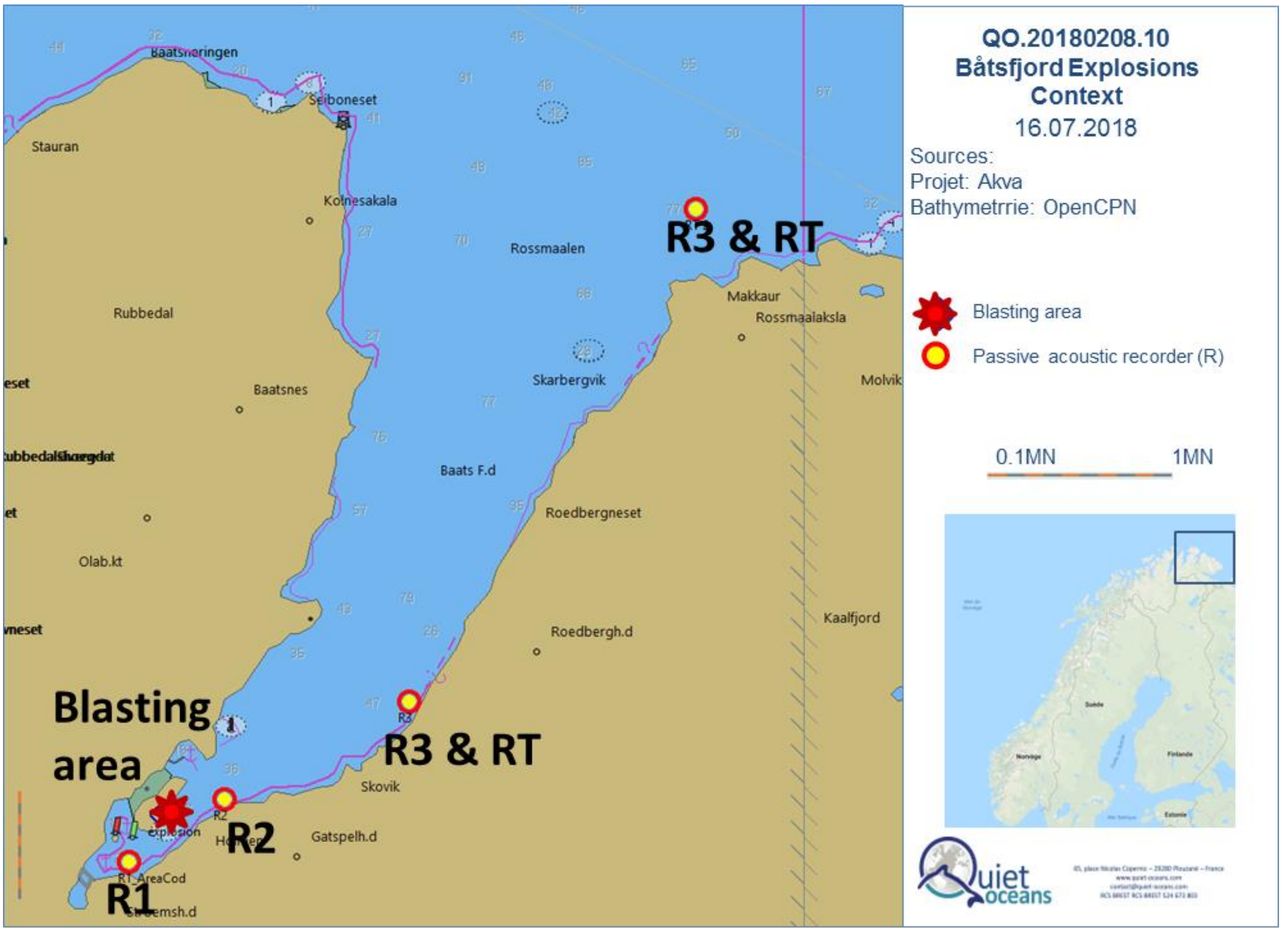


Table 1: Blasting and acoustic recorders locations

Name	Latitude	Longitude	Immersion from surface	Water depth
Basting area	70° 37.7087' N	029° 43.1802' E	NA	~7 m
R1 (Cod hotel)	70° 37.3064' N	029° 42.3242' E	11 m	23 m
R2	70° 37.8460' N	029° 44.8333' E	14 m	28 m
R3 (first explosion)	70° 38.6957' N	029° 49.6565' E	15 m	~30 m
RT (first explosion)	70° 38.6957' N	029° 49.6565' E	8 m	~30 m
R3	70° 42.9646' N	029° 57.1663' E	30 m	~70 m
RT	70° 42.9646' N	029° 57.1663' E	8 m	~70 m

II.3. Times of recording

Figure 7Table 2 indicates the exploitable recording times of acoustic instrumentation for all blasting operations.

Table 2: Exploitable recording times

Point name	Recorder Name	Id Channel	Starting time UTC (HHMMSS)	Ending time UTC (HHMMSS)
Shot D2_S01 – 24 April 2018 08:34 UTC				
R1	ENR-017	01	070300	161700
R2	ENR-015	01 02	070300	161700
R3	ENR-018	01	070300	161700
RT	icl1738	01	080000	085400
Shot D2_S02 – 24 April 2018 12:34 UTC				
R1	ENR-017	01	121245	130000
R2	ENR-015	01 02	070300	161700
R3	ENR-018	01	070300	161700
RT	icl1738	01	121245	130000
Shot D2_S03 – 24 April 2018 15:44 UTC				
R1	ENR-017	01	151700	160000
R2	ENR-015	01 02	070300	161700
R3	ENR-018	01	070300	161700
RT	icl1738	01	151700	160000
Shot D3_S01 – 25 April 2018 19:33 UTC				
R1	ENR-017	01	191705	194300
R2	ENR-015	01 02	134200	194300
R3	ENR-018	01	134200	194300
RT	icl1738	01	191700	194300
Shot D4_S01 – 26 April 2018 14:56 UTC				
R1	ENR-017	01	142500	150500
R2	ENR-015	01 02	130500	153000
R3	ENR-018	01	130500	153000
RT	icl1738	01	142500	150500

II.4. Support vessel for the measurement

The vessel used for the deployment of the acoustic moorings is "Havna" (Figure 3).

Figure 3 : Support vessel used for the experiment.

II.5. Blasting information

For each blasting operation, in a preliminary step, a drilling operation was done in order to place the charges a few meters below the surface of the rocky bottom (Figure 4).

Each explosion is composed of a set of regularly spaced holes called a "well" (Figure 5). In each hole, the charge per hole is a multiple of the unit charge (2.1 kg of dynamite). For each blasting, the number of holes implemented is different. Holes inside a "well" are sorted in several groups. For each group, the different holes blast simultaneously. But between each group, a micro-delay of several milliseconds is set. On 24 April 2018, the micro-delay was set to 50ms. On 25 and 26 April 2018, the micro-delay was set to 25ms.

Information about each explosion has been collected in order to make possible the interpretation of the underwater acoustic levels. Table 3 is a synthesis of the blasting information for each explosion. More detailed information about the hole, charge and micro-delay configurations are given in sections II.5.1. to II.5.5.

On the first day (24 April), three explosions were set in well 1. On the second day (25 April), one explosion was done in well 2. And the last day (26 April), one explosion was done in well 3 (Figure 5). Before each explosion, remaining material from the previous blasting was removed. At the time of the writing of this report, it was not reported if each hole is filled up with gravel (or other sediment) to the level of the substrate.

Figure 4: Schematic view of the blasting location (on top)

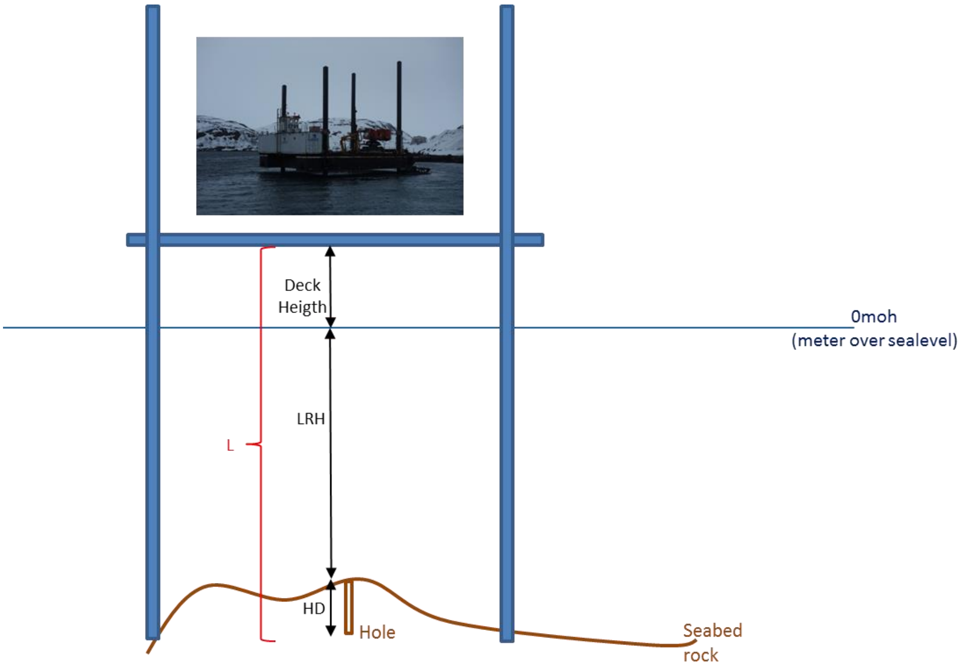


Figure 5 : Schematic representation of each well (red stars correspond to holes actually blasted)

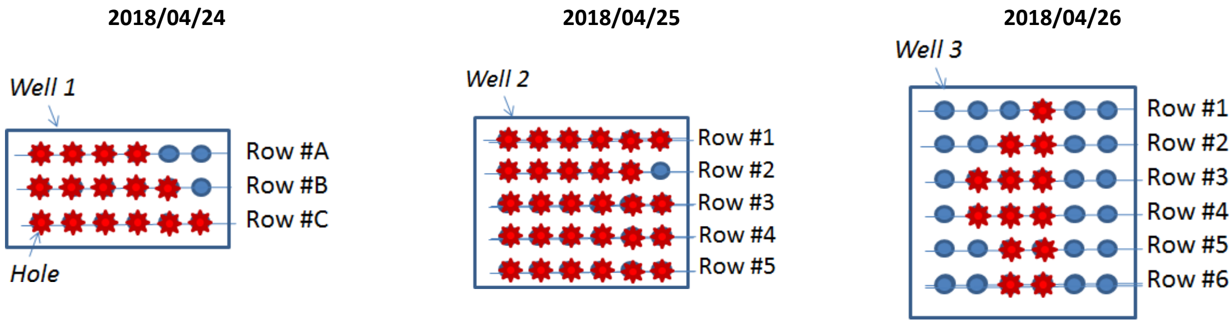


Table 3: General information on each blasting

Shoot Id	Day	Time UTC	Well Id	Nb of group	Micro-delay (ms)	Nb of holes	Row Id	Total charge (Kg dynamite)
D2_S01	2018/04/24	08:34	1	2	50	4	A	56,7
D2_S02	2018/04/24	12:34	1	2	50	5	B	75.6
D2_S03	2018/04/24	15:44	1	2	50	6	C	109.2
D3_S01	2018/04/25	19:33	2	15	**25**	29	1 to 5	529.2
D4_S01	2018/04/26	14:56	3	5	25	13	1 to 6	144.9

Table 4: Format to describe the information for each hole

	G	
LRH	⊗	DP
	HD	HC

G = Group Id
LRH = Laser rock height
DP = Number of dynamite pieces of 2,1 Kg
HD = Hole depth
HC = Hole charge in Kg dynamite

II.5.1. Blasting D2_S01

For this blasting, the explosive is divided in two groups. The first group, number 29, is composed of three holes (hole 1: 4*2.2 kg, hole 2: 5*2.1 kg, hole 3: 8*2.1 kg). The second group, number 30, ignited 50 ms after the first one, is composed of one hole (hole 4: 10*2.1 kg).

Row	Area		Hole 1			Hole 2			Hole 3			Hole 4			Hole 5			Hole 6	
			29			29			29			30			30			-	
A		17,89	⊗	4	17,37	⊗	5	15,64	⊗	8	14,82	⊗	10	-	⊗	-	-	⊗	-
			2,45	8,4		2,97	10,5		4,73	16,8		5,52	21		-			-	

II.5.2. Blasting D2_S02

Row	Area		Hole 1			Hole 2			Hole 3			Hole 4			Hole 5			Hole 6	
			30			29			29			29			30			-	
B		18,35	⊗	4	17,51	⊗	6	17,49	⊗	6	15,59	⊗	9	14,63	⊗	11	-	⊗	-
			2,46	8,4		3,33	12,6		3,35	12,6		5,25	18,9		6,21	23,1		-	

II.5.3. Blasting D2_S03

Row			Hole 1			Hole 2			Hole 3			Hole 4			Hole 5			Hole 6	
			30			29			29			29			30			30	
C		17,47	⊗	5	17,10	⊗	6	15,68	⊗	8	14,82	⊗	10	13,88	⊗	11	13,39	⊗	12
			2,87	10,5		3,24	12,6		4,66	16,8		5,52	21		6,46	23,1		6,95	25,2

II.5.4. Blasting D3_S01

Row	Area		Hole 1			Hole 2			Hole 3			Hole 4			Hole 5			Hole 6	
			3			2			1			1			2			3	
1	38	16,6	⊗	5	15,7	⊗	7	15	⊗	8	14,6	⊗	9	14,2	⊗	10	13,3	⊗	11
			3,25	10,5		4,15	14,7		4,85	16,8		5,25	18,9		5,65	21		6,55	23,1
			6			5			4			4			5			6	
2	39	16,3	⊗	8	15,6	⊗	9	15,2	⊗	10	14,5	⊗	11	13,7	⊗	11	-	⊗	-
			4,55	16,8		5,25	18,9		5,65	21		6,35	23,1		7,15	23,1		-	
			9			8			7			7			8			9	
3	39	16,6	⊗	7	16	⊗	8	15,5	⊗	9	14,7	⊗	10	14,4	⊗	10	13,7	⊗	11
			4,25	14,7		4,85	16,8		5,35	18,9		6,15	21		6,45	21		7,15	23,1
			12			11			10			10			11			12	
4	39	16,8	⊗	7	16,5	⊗	7	16	⊗	8	15,4	⊗	9	15,3	⊗	9	15	⊗	9
			4,05	14,7		4,35	14,7		4,85	16,8		5,45	18,9		5,55	18,9		5,85	18,9
			15			14			13			13			14			15	
5	39	16,8	⊗	7	16,7	⊗	7	16,3	⊗	8	15,5	⊗	9	15,2	⊗	9	15,6	⊗	9
			4,05	14,7		4,15	14,7		4,55	16,8		5,35	18,9		5,25	18,9		5,25	18,9

II.5.5. Blasting D4_S01

Row	Area	Hole 1			Hole 2			Hole 3			Hole 4		
			-			-			-			16	
1	37	-	⊗	-	-	⊗	-	-	⊗	-	17,8	⊗	5
			-			-			-			2,8	10,5
			-			-			16			16	
2	37	-	⊗	-	-	⊗	-	17,3	⊗	5	17,3	⊗	5
			-			-			2,85	10,5		2,85	10,5
			-			17			17			17	
3	36	-	⊗	-	17,6	⊗	5	17	⊗	6	16,7	⊗	6
			-			2,75	10,5		3,35	12,6		3,65	12,6
			-			18			18			18	
4	36	-	⊗	-	18	⊗	4	17,5	⊗	5	16,9	⊗	6
			-			2,35	8,4		2,8	10,5		3,45	12,6
			-			-			19			19	
5	36	-	⊗	-	-	⊗	-	17,5	⊗	5	16,8	⊗	6
			-			-			2,85	10,5		3,55	12,6
			-			-			20			20	
6	36	-	⊗	-	-	⊗	-	17,5	⊗	5	17	⊗	6
			-			-			2,85	10,5		3,35	12,6

II.6. Acoustic instrumentation deployed

The acoustic instrumentation includes four independent systems (Figure 6):

- One two-channel autonomous recorder set up for “high and low levels” to measure intense sounds and ambient noise;
- Two single-channel autonomous recorders set up for “classical levels” to measure classical sounds (ships) and ambient noise;
- One Iclisten autonomous and real-time recorder for “low levels” to measure intense sounds at large distance and ambient noise.

Table 5 shows the reception ranges of the proposed equipment and demonstrates that using diverse equipment allows the measurement of all ranges of noise levels, from ambient to intense noises.

Figure 6: Iclisten (left) and SM3M (right) recorder systems.

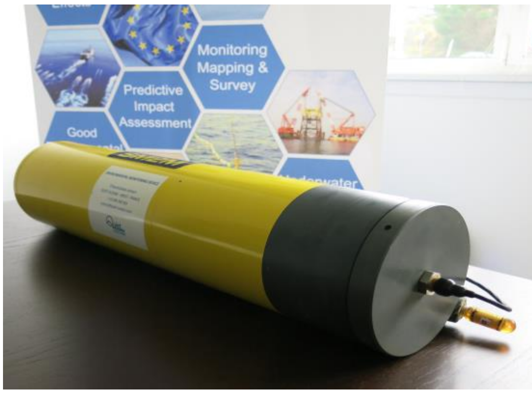


Table 5: Minimum and maximum range for Sound Pressure Levels (SPL) for each recorder.

Equipment	Single-channel SM3M	2-channel SM3M	Single-channel Iclisten
SPL min (dB ref 1µPa)	83	159	83
SPL max (dB ref 1µPa)	166	242	174
Dedicated zone	Near/Far (R1 & R3)	Near (R2)	Far (RT)

II.6.1. Description of the single-channel Iclisten

In order to perform continuous hydrosound measurement at large distances and in real-time, we use the single-channel Iclisten acoustic recorder manufactured by Oceans Sonics. The technical characteristics of this recorder are detailed in Table 6. The maximum selectable sample frequency is 512 kHz, enabling to use the complete bandwidth of the hydrophone (characteristics in Table 5) and to capture the expected steep variation of the pressure.

Table 6: Technical characteristics of the Iclisten omnidirectional hydrophone

Hydrophone	Omnidirectional
Frequency band	10Hz to 180kHz 10 Hz to 80 kHz with variability less than 2 dB
Maximum sample frequency	512 kHz
Sensibility	-170.4 dB re: 1V/µPa
Gain	NA
Audio files format	Wav
Autonomy for continuous measurement	10 hours
Length	267 mm
Diameter	45 mm
Weight	0.3 kg
Maximum operating depth	200 m
Operating temperature range	-20°C to 50°C

II.6.2. Description of the single-channel SM3M

In order to perform continuous hydrosound measurement at large distances, we use two single-channel SM3M acoustic recorders (Figure 3) manufactured by Wildlife Acoustics Inc. The technical characteristics of these recorders are detailed in Table 7. The maximum selectable sample frequency is 384 kHz enabling to use the complete bandwidth of the HTI99-HF hydrophone (characteristics in Table 5) and to capture the expected steep variation of the pressure.

Table 7: Technical characteristics of the SM3M recorder and HTI SPL omnidirectional hydrophone (near area “ambient noise”)

Hydrophone	HTI99HF, Omnidirectional
Frequency band	10Hz to 180kHz 10 Hz to 80 kHz with variability less than 2 dB
Maximum sample frequency	384 kHz
Sensibility	Without Pre-Amp: -201 dB re: 1V/µPa (8.9V/bar) With Pre-Amp: Max -165 dB re: 1V/µPa (562V/bar), Min -240 dB re: 1V/µPa (0.1V/bar)
Gain	0-12 dB
Audio files format	Wav
Autonomy for continuous measurement	Minimum 30 days with Alkaline batteries
Length	79.4 cm
Diameter	16.5 cm
Weight	13.5 kg filled with 32 batteries
Maximum operating depth	200 m
Operating temperature range	-20°C to 50°C

II.6.3. Description of the two-channel SM3M

The recorder used to record intense noise at the shortest ranges is the two-channel SM3M acoustic recorder manufactured by Wildlife Acoustics Inc. in the United States. It has the same shape than the previous one.

Two hydrophones are connected to the recorder:

- one is a HTI High SPL omnidirectional with low sensitivity, specifically designed to record and characterize high acoustic pressure levels (SPL) thanks to a hydrophone with a sensitivity of -240dB ref. 1 V / µPa (characteristics in Table 5);
- the second channel is connected to a more sensitive hydrophone in order to also measure lower levels such as ambient noise levels.

Table 8: Technical characteristics of the SM3M recorder and HTI High SPL omnidirectional hydrophone (far area "high levels" recorder)

Hydrophone	HTI High SPL omnidirectional
Frequency band	10Hz to 180kHz 10 Hz to 80 kHz with variability less than 2 dB
Maximum sample frequency	256 kHz
Sensibility	-240dB ref. 1 V / µPa on channel 1 -163.9 ref. 1 V / µPa on channel 2
Gain	0-12 dB
Audio files format	Wav
Autonomy for continuous measurement	Minimum 30 days with Alkaline batteries
Length	79.4 cm
Diameter	16.5 cm
Weight	13.5 kg filled with 32 batteries
Maximum operating depth	200 m
Operating temperature range	-20°C to 50°C

II.7. Deployment setup

Figure 7 shows the type of deployment implemented for each device: the SM3M recorders are deployed on a fixed mooring while the IcListen real-time device is deployed from the support vessel.

Figure 7: Deployment configuration for acoustic recorders

SM3M deployment (R1,R2,R3)	Iclisten deployment (RT)

Chapter III. Ambient noise analysis

In order to estimate the broadband ambient noise level, the statistical levels have been analysed based on the three days of monitoring. We observe a same trend between the first and the last day, and a large period with significantly lower levels during the second day of measurement.

Figure 8 shows the temporal variation of ambient noise during this period and Table 9 gives statistical values in percentile. 95% of the time, the Sound Pressure Level of the ambient noise is higher than in 97 dB ref 1µPa² and exceed 130.4dB ref 1µPa² for 5% of the time. The median value measured across the three days is 119.7 dB ref 1µPa².

Figure 8: Broadband level (11Hz to 39kHz) received during experiment

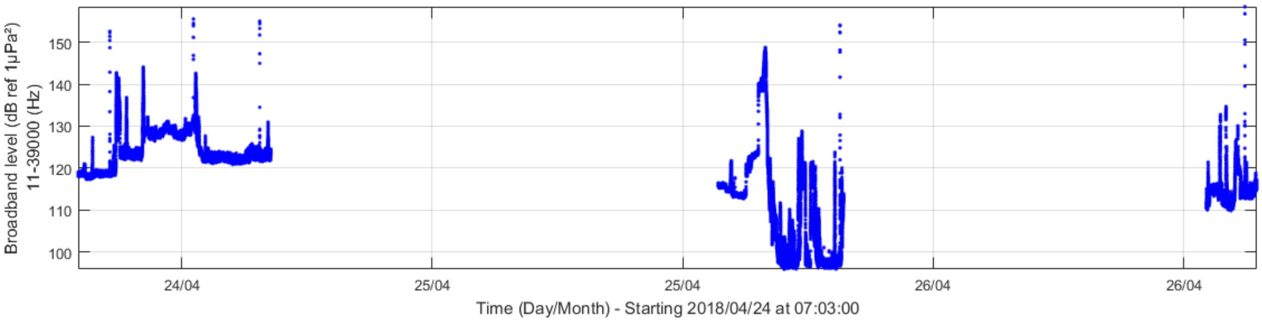


Table 9: Statistics of broadband ambient noise over the period.

	All the time		Half of the time			Rarely	
Percentile (% of time)	95 %	90 %	75 %	50 %	25 %	10 %	5 %
Ambient noise in the 11Hz-39kHz bandwidth (dB ref. 1µPa²)	97.0	98.3	113.7	119.7	123.4	128.8	130.4

Observed median ambient noise levels are:

- Offshore oceanic area: 100 dB ref 1µPa²;
- Coastal area: 105 dB ref 1µPa²;
- Large port area: 100 to 105 dB ref 1µPa².

The ambient noise measured in Båtsfjord is in average 10 dB higher than in other port areas comparable to a fjord. The factors of this difference should be the almost continuous presence of at least a motor vessel in a fjord area which sediment has higher reflection properties than other site configurations. Figure 9 shows the shipping density in Båtsfjord and in the North Coast area of Norway. Båtsfjord appears to be one of the busiest fjord areas for shipping.

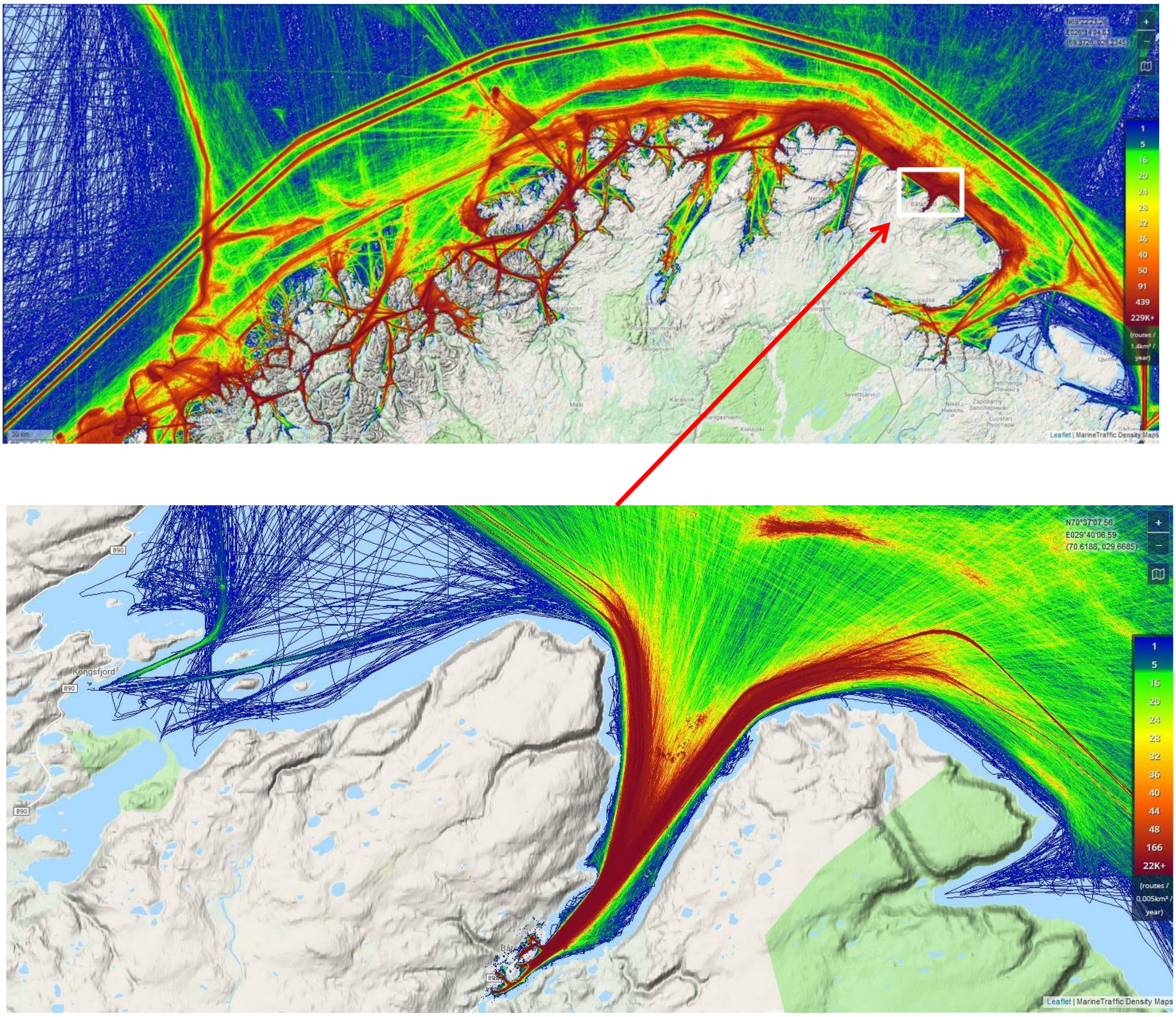


Figure 9: Shipping density in the Norwegian North Coast area (above) and in Båtsfjord area (below). Source: Marine Traffic.

Chapter IV. Cetaceans presence

Since not required by the client, the search for cetacean presence has not been the subject of a specific analysis on all available acoustic data. Visual observations were made from the support vessel by Quiet-Oceans team on site and some spot checks were made on the recorded acoustic data.

IV.1. Expected species

Table 10 summarizes a non–exhaustive list of marine mammals likely to be present in the Norwegian waters (Kaschner, 2016). The 24 species that are likely to be present has been classified according to the family they belong to:

- Balenopteridae family includes rorquals species and the Humpback Whale (*Megaptera novaeangliae*);
- Delphinidae family includes dolphins, killer whales and pilot whales species;
- Phocoeniade family includes porpoises species;
- Ziphiidae family includes beaked whales species;
- Phocidae family includes seals species and the sea elephant (*Mirounga sp.*).

Table 10: Common species present in Norwegian waters

Family	Species	Common Name
Balaenopteridae	Balaenoptera acutorostrata	Northern minke whale
	Balaenoptera borealis	Sei whale
	Balaenoptera musculus	Blue whale
	Balaenoptera physalus	Fin whale
	Megaptera novaeangliae	Humpback whale
Delphinidae	Delphinus delphis	Common dolphin
	Globicephala melas	Long-finned pilot whale
	Grampus griseus	Risso's dolphin
	Lagenorhynchus acutus	Atlantic white-sided dolphin
	Lagenorhynchus albirostris	White-beaked dolphin
	Orcinus orca	Killer whale
	Tursiops truncatus	Bottlenose dolphin
Monodontidae	Monodon monoceros	Narwhal
Mustelidae	Lutra lutra	Eurasian river otter
Odobenidae	Odobenus rosmarus	Walrus
Phocidae	Cystophora cristata	Hooded seal
	Erignathus barbatus	Bearded seal
	Halichoerus grypus	Grey seal
	Phoca vitulina	Harbour seal
	Pusa hispida	Ringed seal
Phocoenidae	Phocoena phocoena	Harbour porpoise
Physeteridae	Physeter macrocephalus	Sperm whale
Ziphiidae	Hyperoodon ampullatus	North Atlantic bottlenose whale
	Mesoplodon bidens	Sowerby's beaked whale

IV.2. Cetacean observations

During experiments, observations were made from the vessel support around each location. One sighting of harbour porpoise occurred before blasting D2_S02 and D2_SO3 during 15 minutes at location 70° 42.9646’ N, 029° 57.1663’ E (RT recorder position at entrance to the fjord) (Figure 10). During blasting, no sighting of cetacean was made around the vessel support. Likewise, after each blasting, no sighting happened around the vessel support.

On recorded acoustic data of R3 hydrophone, before shot D2_S02 (12h34 UTC), we search typical acoustic signature of Harbour Porpoise before, during and after blasting. We observe several clicks on spectrograms with specific characteristics of this specie (impulsive signal in bandwidth 125 to 160 kHz).

The same process is applied on all records of the hydrophone R3. Figure 11 shows Harbour Porpoise detection clicks and blasting instants. As previously noted, we observe Harbour Porpoise presence (27 clicks over 5min) before blasting D2_S02 (12h34 UTC).

Before the third blasting D2_S03 (15h44 UTC), we detect high presence of harbour porpoise with 620 clicks over 5min. This presence is confirmed during and after blasting with 100 clicks over 5min. Then, for the following shots, no presence of harbour porpoise are detected with this passive acoustic recorder

The thresholds of sensitivity of marine mammals are given in Table 12.

Figure 10: Harbour porpoise observation (position 70° 42.9646’ N, 029° 57.1663’ E, 15’ before shot D2_S02)

Table 11: Typical spectrogram with harbour porpoise clicks (20180424 11h57 UTC on R3 recorder)

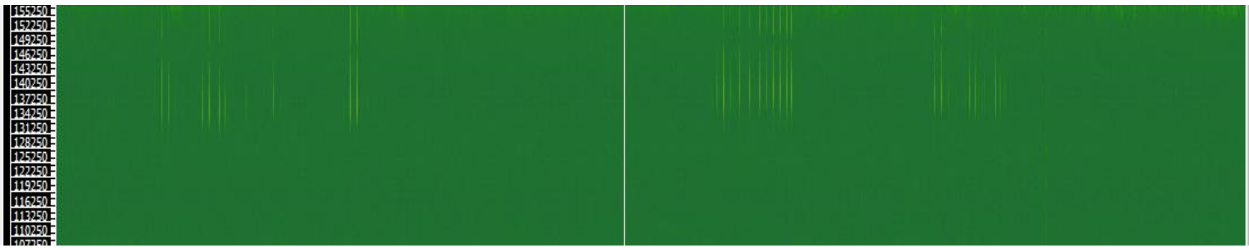
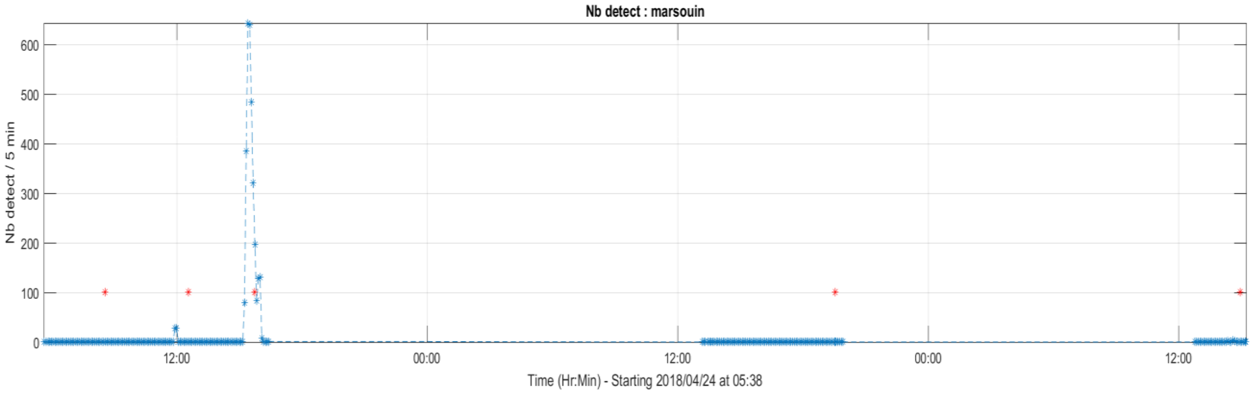


Figure 11: Harbour porpoise clicks (blue dot) and blasting (red star)



Species group	Abbr.	Frequency range of perception (kHz)	Impulsive noise SEL (dB ref. 1µPa²s)	
			TTS	PTS
Low frequency cetaceans	LF	0.2-19	168	183
Mid frequency cetaceans	MF	8.8-10	170	185
High frequency cetaceans	HF	12-140	140	155
Phocids (true seals)	P	1.9-30	170	185

Table 12: Underwater noise sensitivity thresholds of species groups. Sources: (NOAA 2016)
TTS: Temporary Threshold Shift, PTS: Permanent Threshold Shift

Chapter V. Physical analysis of explosion

V.1. Objective

The objective of the physical analysis of the explosive source is to calculate metrics that characterize the received and emitted sound levels.

V.2. Received levels

Table 13 gives received underwater acoustic levels for each blasting at each location of recorder. In comparison between each recorder location, we can observe significant variations of acoustic levels close to 215 dB ref 1µPa (SPL peak-peak) at R2 location (1,100m and direct path) and a decrease of 40 dB at R1 location (900m and reverberant paths). This decrease, at short distance due to the bathymetric feature, is equivalent to the decrease observed at large distance in R3 (13,100m and direct path).

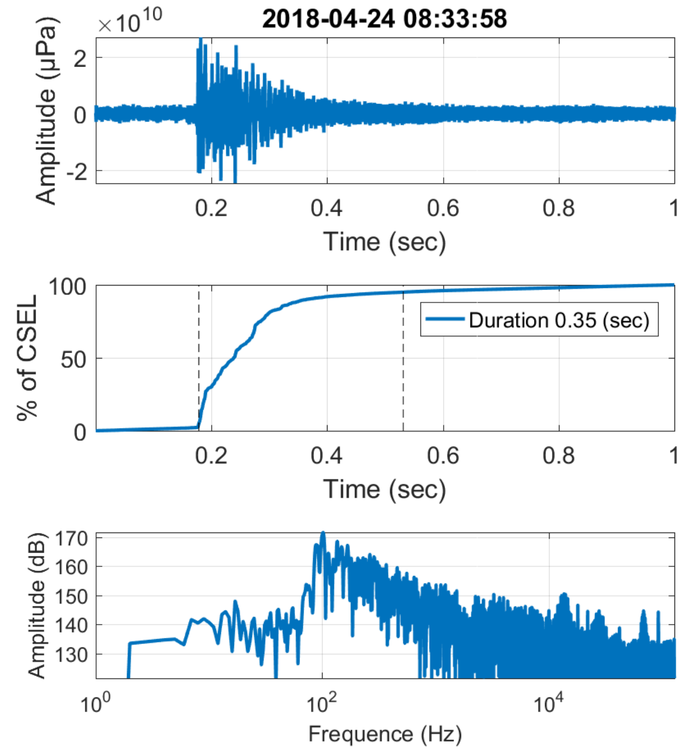
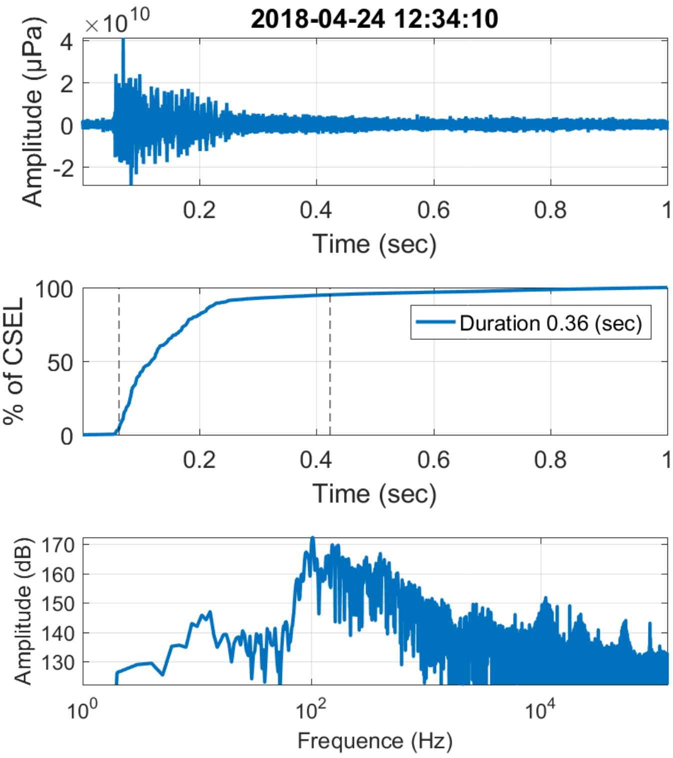
At the same location, the difference between explosive dynamite charges (56 to 529 kg) induces small differences on underwater acoustic levels. For example, the SPL_{pk-pk} is increased by less than 1 dB while the Sound Exposure Level (SEL) shows a raise of 5dB though. These results can be explained by the temporal spreading induced by the use of micro-delays between each group of charges. Indeed, without micro-delay each acoustic level produced by each charge is summed up synchronously. This does not happen when micro-delay is used, which spreads the peaks levels over time. For blasting D2_S01, the number of groups is two while for blasting D3_S01, the number of group is 15. For each group, the total sum of blasting dynamite simultaneously is almost equivalent, which explains the similar intensity of the SPL_{pk-pk}. Thus, the SEL increase is mainly explained by the number of groups involved.

Table 14 shows the typical signature of blasting at location R2 (1,100m and direct path). The triptych shows the temporal signal, the significant duration T_{90} in second, and spectrum distribution of the acoustic energy. For the three first blasting operations, the temporal signatures are similar in form and duration. In this context, the spectrum shows a maximum of energy for frequencies ranging from 80 to 200Hz. The significant attenuation of low frequencies below 80 Hz can be explained by the water height and bottom properties, which induce a cut-off frequency of the sound waves (Brekhovskikh, 1960). For the Båtsfjord site, an average water depth close to 7m and a bedrock with a longitudinal velocity of 2,000m/s generate a theoretical cut-off frequency of about 80Hz. Thus, this bathymetric context is unfavourable to the propagation of highly energetic low frequency waves. The D3_S01 blasting generates a very long time-stretched signal but shape of the spectrum remains similar. The temporal signal shows clearly the multiple explosive phases of each group.

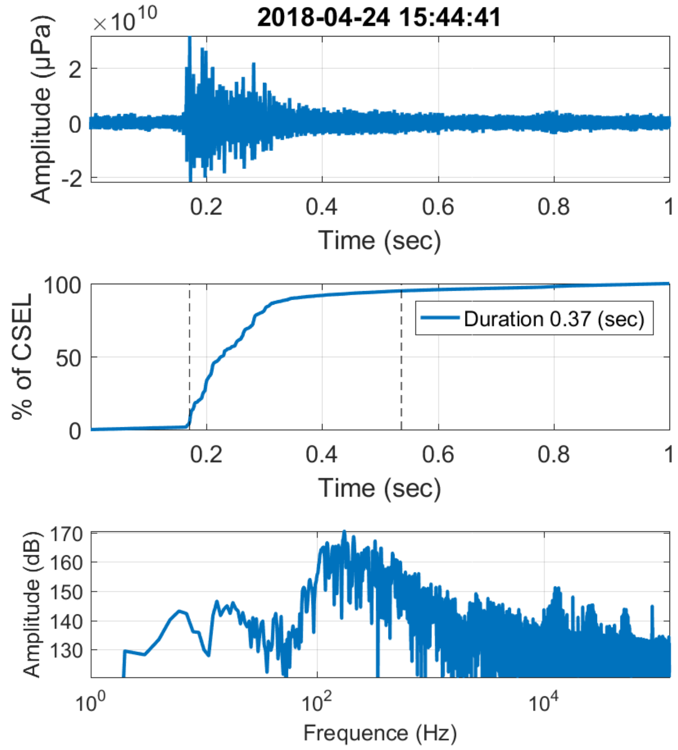
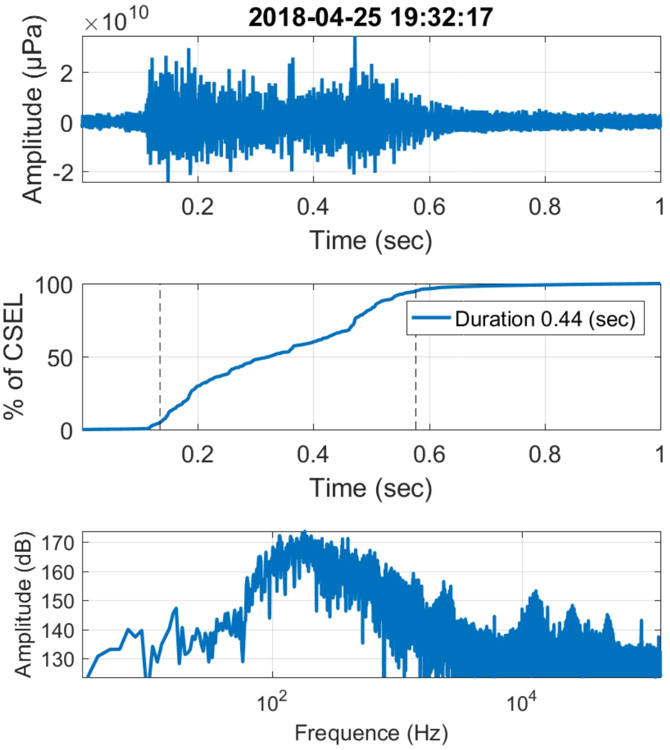
Table 13: Received acoustics levels for each explosion[1]

Shot	Date	Blasting time UTC	Recorder	Location	Distance from blasting point (m)	SPL pk-pk (dB ref 1µPa) Unweighted	SPL 0-pk (dB ref 1µPa) Unweighted	SPL rms (dB ref 1µPa) Unweighted	SEL (dB ref 1µPa²s) Unweighted
D2_S01	24/04/2018	08:34:00	ENR-018	R1	900	177.3	171.9	154.1	153.6
			ENR-015	R2	1100	214.3	208.6	192.2	188.2
			ENR-017	R3	4500	*NA*	*NA*	*NA*	*NA*
			icl1738	RT	4500	*NA*	*NA*	*NA*	*NA*
D2_S02	24/04/2018	12:34:00	ENR-018	R1	900	181.6	176.4	158.8	157.0
			ENR-015	R2	1100	216.8	212.3	193.7	189.8
			ENR-017	R3	13100	166.1	161.6	135.0	134.0
			icl1738	RT	13100	172.0	167.7	151.0	146.0
D2_S03	24/04/2018	15:44:50	ENR-018	R1	900	179.2	175.4	157.8	156.3
			ENR-015	R2	1100	214.5	210.0	192.6	188.7
			ENR-017	R3	13100	172.6	166.9	155.8	147.7
			icl1738	RT	13100	167.3	161.5	146.3	145.9
D3_S01	25/04/2018	19:32:00	ENR-018	R1	900	176.0	171.0	154.9	154.8
			ENR-015	R2	1100	215.0	210.8	196.1	193.0
			ENR-017	R3	13100	170.8	165.9	154.7	152.1
			icl1738	RT	13100	174.6	169.2	158.6	155.6
D4_S01	26/04/2018	14:56:00	ENR-018	R1	900	191.3	188.3	166.3	162.8
			ENR-015	R2	1100	*NA*	*NA*	*NA*	*NA*
			ENR-017	R3	13100	171.4	166.4	155.5	149.9
			icl1738	RT	13100	171.8	166.7	155.7	150.9

Table 14: Temporal signature in µPa, significant duration in sec and power spectral density in dB ref 1µPa²/Hz at 900m from blasting area (recorder ENR-015 in R2)

Blasting D2_S01	Blasting D2_S02
	

[1] *NA value indicates not available data due to clipping or technical problem*

Blasting D2_S03	Blasting D3_S01
	

V.3. Estimation of source levels

In order to estimate the source level induced by these blasting operations, we extrapolate values from measurement done at short distances (R2 location). In this environmental context (complex bathymetry), the transmission loss can be approximated by a mix with cylindrical and spherical laws $K.\log_{10}(r)$ where K=17 and r is the distance from the blast. In this case, we obtain 267.7 dB ref 1µPa SPL@1m peak-peak maximum value and 247.7 dB ref 1µPa@1m SPL_{rms} maximum value. Using this approximation, the strong attenuation of low frequencies (<80Hz) induced by cut-off frequency is not taken into account.

For better accuracy, a propagation model needs to be used to estimate the transmission loss for each frequency. In this case, the environmental data (bathymetry, sound speed profile, bottom properties, and surface roughness) needs to be known with a fair resolution (Collins M. , Cederberg, King, & Chin-Bing, 1996), (Porter & Reiss, 1984). Here, the environmental data with high resolution are not available.

Chapter VI. Footprint analysis

The objective of this chapter is to evaluate the footprint induced by blasting operations in the context of Båtsfjord. Using the measurement at different locations and statistical ambient noise, we can estimate the limit of perception of the blast sounds.

The statistical ambient noise values come from Table 9. The acoustics levels recorded at R2 and R3 locations (respectively 1,100 and 13,100 m along the direct path) allow us to extrapolate statistical limits of perception.

Table 15 gives the statistical limit of underwater blasting perception. This limit depends on ambient noise level. The median footprint estimated by this method is 174 km. This limit assumes that there is no other source of noise over this distance that could mask the explosive contribution. In other words, it is assumed that the ambient noise is constant.

Table 15: Limit of statistical footprint of blasting

	Percentile 90%	Percentile 50%	Percentile 10%
Ambient noise (dB ref 1µPa²)	98.3	119.7	128.8
Distance (km)	400	174	96

Chapter VII. Risks for fishes

This chapter assesses from the previous results the impact on fish potentially present at the vicinity of the blasting sources. There are currently two ways to evaluate the risk toward fishes:

- (Popper, et al., 2014) which has defined thresholds values that would induce mortality and potential lethal injury that enable the calculation of a risk area;
- Guidelines for the Use of Explosives In or Near Canadian Fisheries Waters (Hopky, 1998).

VII.1. Risk assessment based on threshold values

(Popper, et al., 2014) has defined thresholds values that would induce mortality and potential lethal injury that enable the calculation of a risk area as reported in Table 16. For other disturbances (recoverable injury, temporary threshold shift, masking and behaviour), Popper has defined terminology in order to classified the relative risk as high, moderate and low. For this disturbance, in the absence of thresholds, Popper defined the “high” risk at near and intermediate distance from source. The risk is considered “low” at large distance. But no assumptions are made about explosive source and received levels because there are insufficient data to quantify what these distances might be (Popper, et al., 2014).

Using these thresholds based on the $SPL_{0\text{-}pk}$ measured during the blasting, mortality and potential mortal injury area occurs at maximum ranges from 258 to 359m depending on the threshold value.

At the Cod hotel location (R1 recorder), the $SPL_{0\text{-}pk}$ acoustic level measured (maximum 188.3 dB ref 1µPa for last blasting) shows for all blasting shots lower values than the known thresholds defined by (Popper et al. 2014).

However, it is very likely that beyond this distance, temporary damage or behaviour modification occurs that may not have an immediate effect on the species, but that may lead to an increased mortality on the longer term if they are exposed to a significant number of blasting shots over time.

For eggs and larvae, the threshold of mortality or potential mortal injury is expressed in peak particle velocity (in mm/s) and the limit is 13 mm/s. The measurement of particle velocity needs specific equipment that has not been deployed during this study.

Table 16: Thresholds for fish for blasting activity (Popper, et al., 2014)

Specie	Hearing sensitivity (kHz)	Explosions	
		Unweighted $SPL_{0\text{-}pk}$ in dB ref. 1µPa	
		Mortality and potential mortal injury	
All Fish : **(no swim bladder / where swim bladder is not involved in hearing / where swim bladder is involved in hearing)**	<1kHz	229	234

VII.2. Risk assessment based on Canadian Fisheries guidelines

The guidelines for the Use of Explosives In or Near Canadian Fisheries Waters (Hopky, 1998) indicate a way to estimate the risk area based on:

- ✓ The weight of individual charges: X kg;
- ✓ The number of holes detonated/delay: N;
- ✓ The weight of charge/delay: W = X*N kg.

VII.2.1. Risk for eggs and larvae

$R= W^{0.5}$ (13/100) is the setback distance required to meet the peak particle velocity (VR) guideline of 13 mm•sec. where W is the weight of charge/delay and R is the distance in meter.

In the case of the instantaneous maximum charge used in this project (58.8 kg of dynamite for shots D2_S03 group 30), we obtain a risk distance of 115m around the explosive source. In comparison with Popper criteria, this distance is greatly underestimated.

VII.2.2. Risk for fish

In order to not exceed the overpressure limit 100kPa, the depth to which the charge must be buried is defined by using:

$$R = W^{0.5} K$$

where K is the substrate type and R is the minimal depth/substrate in meters.

SUBSTRATE TYPE	K
Rock	5.03
Frozen Soil	3.2
Ice	2.1
Saturated Soil	2.13
Unsaturated Soil	0.98

Implementing Canadian Fisheries guidelines on the blasting D2_S03 group 30 would lead to bury charges at a depth greater than 38m. It is of course not practically possible. The solution to meet these guidelines would be to decrease the charge by blasting it in several groups.

Chapter VIII. Recommendations

Based on the levels measured during this series of explosions, and based on the scientific knowledge about the effect of sound on marine life, the following recommendation can be made:

- Use the minimum amount of charges needed;
- Use micro-delays in order to minimize the peak-to-peak pressure levels;
- Evaluate the risk area around the blasting by implementing preferably modelling techniques that would take into account the bathymetric and sediment features of the marine environment and Popper et al. 2014 criteria. In the case this could not be feasible for technical reasons, use (Hopky, 1998) formulas, knowing that it would likely underestimate the dimension of the risk area;
- Avoid the presence of commercial fish farms in the risk area;
- Implement a soft-start procedure in order to gradually increase the level of sound up to the maximum levels of the operation;
- Implement real-time passive acoustic monitoring and possibly visual observation at least 30 minutes before the start of each operation to insure that no cetacean is present in the area around the blasting in which physiological damage would occur;
- Pursue real-time passive acoustic monitoring and possibly visual observation at least 30 minutes after the blasting to report any abnormal event on marine life.

Chapter IX. Bibliography

[1] Folegot, T., Clorennec, D.,(2014), From Footprint prediction to risk assessment and focused mitigation, Proceedings of the ECS/ASCOBANS/ACCOBAMS Joint Workshop on introducing noise into the marine environment – what are the requirements for an impact assessment for marine mammals ?, European Cetacean Society's 28th Annual Conference, Liege, Belgium, 6th April 2014.

[2] C. Audoly, C. Rousset, E. Baudin and T. Folegot (2016), AQUO Project: Research on solutions for the mitigation of shipping noise and its impact on the marine fauna, a Synthesis of guidelines, International Conference and Exhibition on Underwater Acoustics, Athens, Greece, 2016.

[3] ANSI S1.11-2004: Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters, American National Standard Institute, USA, Reaffirmed by ANSI 2009.

[4] IEC 1995 (EN 61260), Electroacoustics - Octave-band and fractional-octave-band filters, International Electrotechnical Commission, Geneva, Switzerland, 1996.

[5] G. Le Provost and T. Folegot (2018), Seismic Source Characterization in the North Sea, Recovery of Acoustic Equipment in Lorient, Quiet-Oceans, technical report ref. QO.20170712.01.RAP.019.02A.

[6] D. Clorennec, G. Le Provost and T. Folegot (2018), Seismic Source Characterization in the North Sea, Design Proving Document, Quiet-Oceans, technical report ref. QO.20170712.01.RAP.001.04A.

[7] EMODnet, 2012: Seabed substrate data (version 28.6.2012) made available by the EMODnet (European Marine Observation and Data Network) Geology project, funded by the European Commission Directorate General for Maritime Affairs and Fisheries. http://www.emodnet-geology.eu.

[8] Applied Physics Laboratory. (October 1994). *APL-UW High Frequency Ocean Environmental Models HandBook.* Washington DC, USA: University of Washington.

[9] Collins, M. D. (1994). Generalization of the Split-Step Pade. J. Acoust. Soc. Am., 96, 382-385.

[10] Collins, M. D., Kuperman, W. A., & Siegman, W. L. (1995). Parabolic Equation for poro-elastic media. J. Acous. Soc. Am, 98(3), 1645-1656.

[11] Pekeris, C. L., Theory of propagation of explosive sound in shallow water, in Propagation of Sound in the Ocean, Geol. Soc. Am., Mem. 27, 1–112 (1948)

[12] Wenz, G. (1962). Acoustic Ambient Noise in the Ocean: Spectra and Sources. J. Acosut. Soc. Am., 34:1936-1956.

[13] NOAA. (2016). Techincal guidance for assessing the effects of anthropogenic sound on marine mammal hearing - Underwater acoustic thresholds for onset of permanent and temporary threshold shifts. NOAA Technical memorandum NMFS-OPR-55, NOAA.

[14] ICES. (2018). Ecosystem overviews - Greater North Sea Ecoregion. Visited on the 04 26th, 2018, on ICES: http://www.ices.dk/explore-us/Action%20Areas/ESD/Pages/Greater-North-Sea-Key-State-Marine-mammals.aspx

[15] Simar, V., Mélis, B., & Pézeril, S. (s.d.). Guide d'identification et d'observation des mammifères marins en Manche et Mer du Nord. 1-48. (I. Téteghem, Éd.)

[16] Shirihai H., J. B. (2007). Guide des mammifères marins du monde. Paris, France: Delachaux & Niestlé SA.

[17] Miller, L., & Wahlberg, M. (2013). Echolocation by the harbor porpoise: life in coastal waters. Frontiers in Physiology, 4.

[18] Richardson, W., Malme, C., Green, C., & Thomson, D. (1995). Marine Mammals and Noise. San Diego, CA: Academic Press.

[19] Tougaard, J., Poulsen, L. R., Amundin, M., Larsen, F., Rye, J., & Teilman, J. (2006). Detection function of T-PODS and estimation of porpoise densities. (T. N. Leeney RH, Éd.) In proceedings of the Workshop on static acoustic monitoring of cetaceans, European Cetacean Society, Special Issue(46).

[20] Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G., & Thompson, P. (2010). Using T-PODs to assess variations in the occurence of coastal bottlenose dolphins and harbour porpoises. *Aquatic Conservation: Marine and Freshwater Ecosystems, 20*(2), 150-158.