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Sensitivity of acoustic propagation to uncertainties in the marine environment as characterized by various Rapid Environmental Assessment methods

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Defence Research and Development Canada   Recherche et développement pour la défense Canada

Canada

Outline

- Motivation and objectives
- Uncertainty and sensitivity metric
- Experimental framework
- Sensitivity results and transmission loss
- Questions and observations

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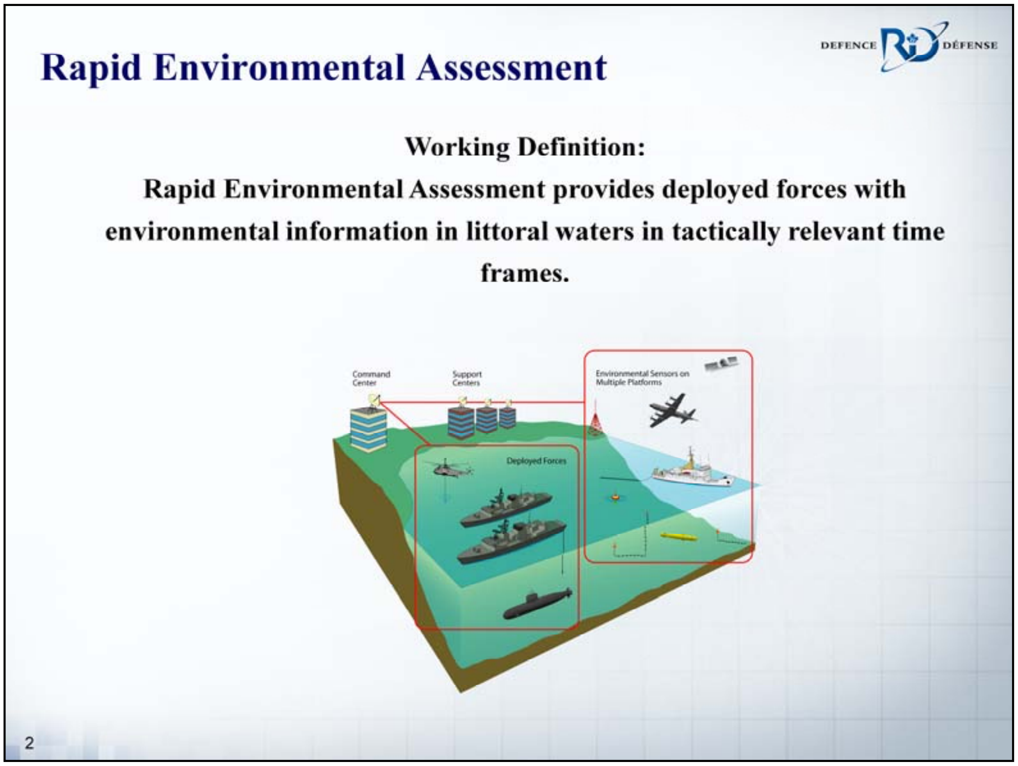
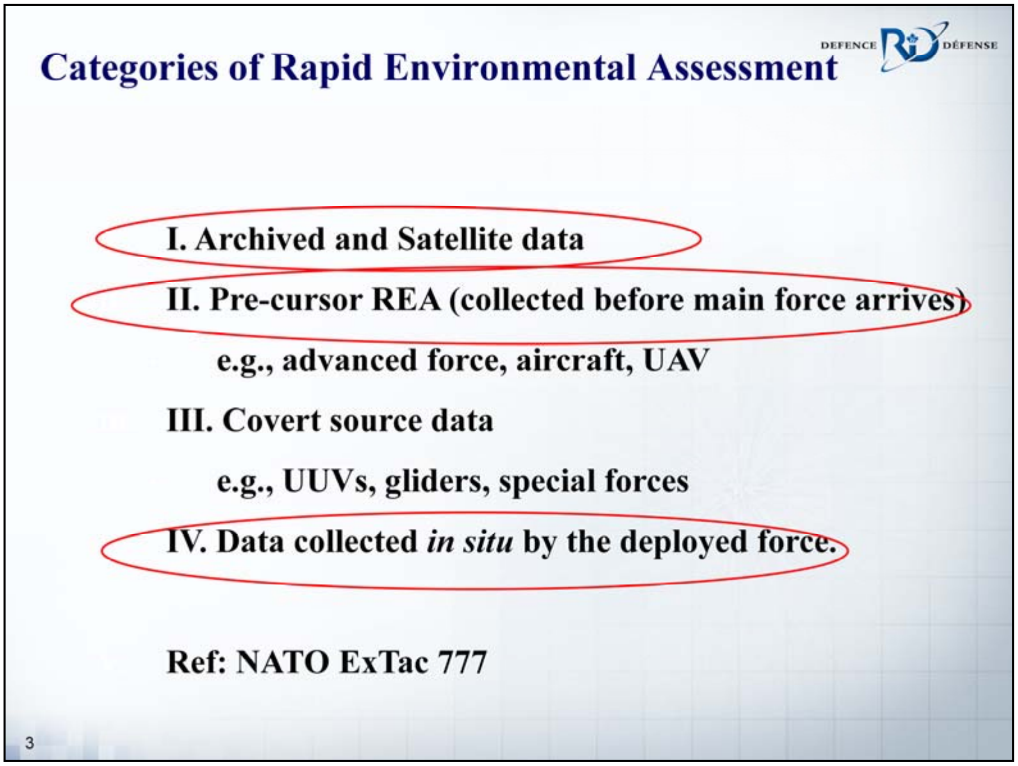
I’ll give a brief overview of our motivation and the objectives we had in undertaking this work, including a description of what we mean by rapid environmental assessment. Then I will present some background material discussing our measurements of the effects of uncertainty via a sensitivity metric. I’ll be focussing on this via the results of environmental and acoustic data acquired during a sea trial last year. Some of the results from that experiment raise some questions concerning our work that tie in to issues discussed during this conference, as well as giving rise to a few general observations.

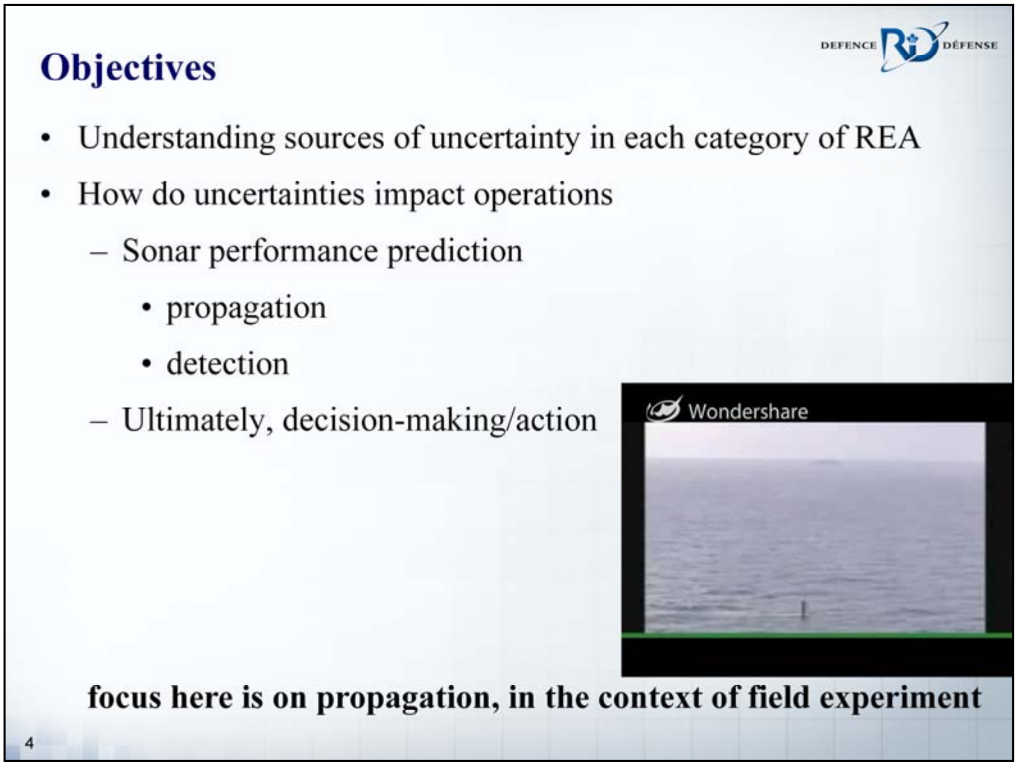


Rapid Environmental Assessment provides deployed forces with environmental information in littoral waters in tactically relevant time frames. The environmental data collected can come from historical sources, remote sensing tools, gliders and autonomous vehicles, or in-situ assets.



NATO ExTac 777 REA into four categories, based on the timeliness of data acquisition, also generally corresponding to ease or covertness of data acquisition. For the purposes of this talk, we'll be categorizing our data into REA categories I, II, and IV

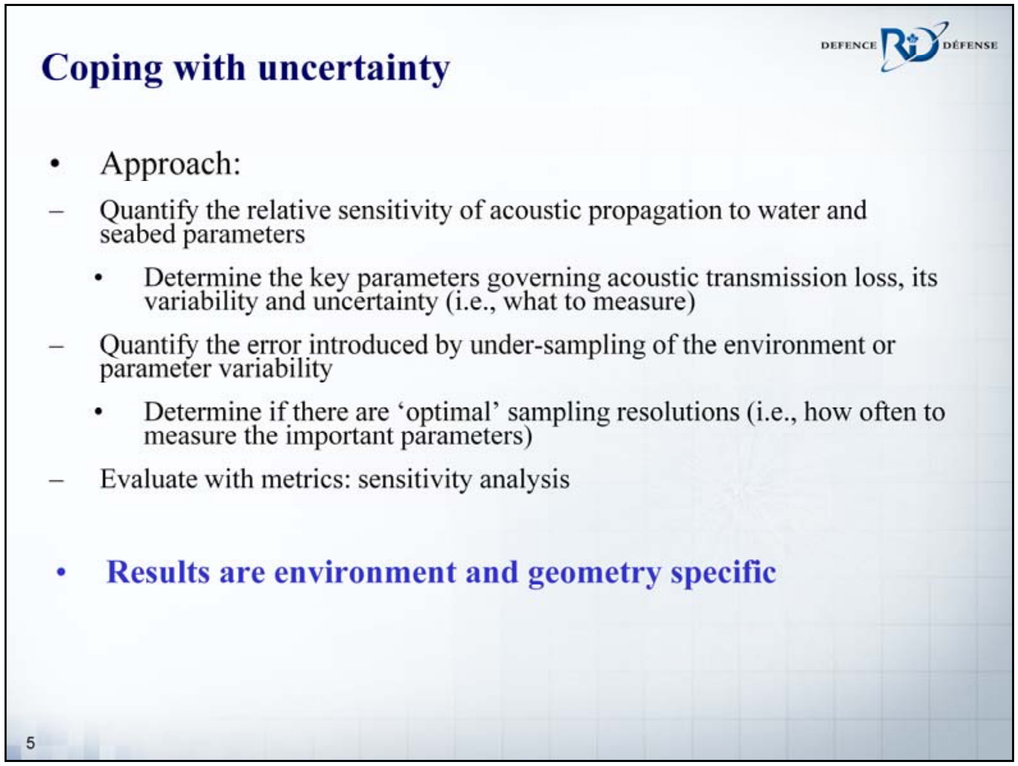
It is expensive in resources and time as we progress through REA categories. We need to know what to measure to have most effective use of resources



Each REA category has uncertainties associated with it. We would like to gain an understanding both of the sources of these uncertainties, and how they translate into impacts on sonar performance prediction, and ultimately decision-making processes.

The endpoint is having best available knowledge for deployed forces, to avoid this “click”

Our focus is on propagation, in the context of a field experiment



Approach:

- Quantify the relative sensitivity of acoustic propagation to water and seabed parameters
  - Determine the key parameters governing acoustic transmission loss, its variability and uncertainty (i.e., what to measure)
- Quantify the error introduced by under-sampling of the environment or parameter variability
  - Determine if there are 'optimal' sampling resolutions (i.e., how often to measure the important parameters)
- Evaluate with metrics: sensitivity analysis

Results are environment and geometry specific

Sensitivity Metrics

Metrics (Dosso et al. 2006, 2007):

Consider sensitivity of pressure field p to perturbations of model or measurable m_j (Gaussian with standard deviation σ).

Non-linear (Monte Carlo) measure:

$$S_{ij} = \frac{\left(\left\langle \left| p_i(m_j + \delta m_j) - p_i(m_j) \right|^2 \right\rangle \right)^{1/2}}{\left| p_i \right|}$$

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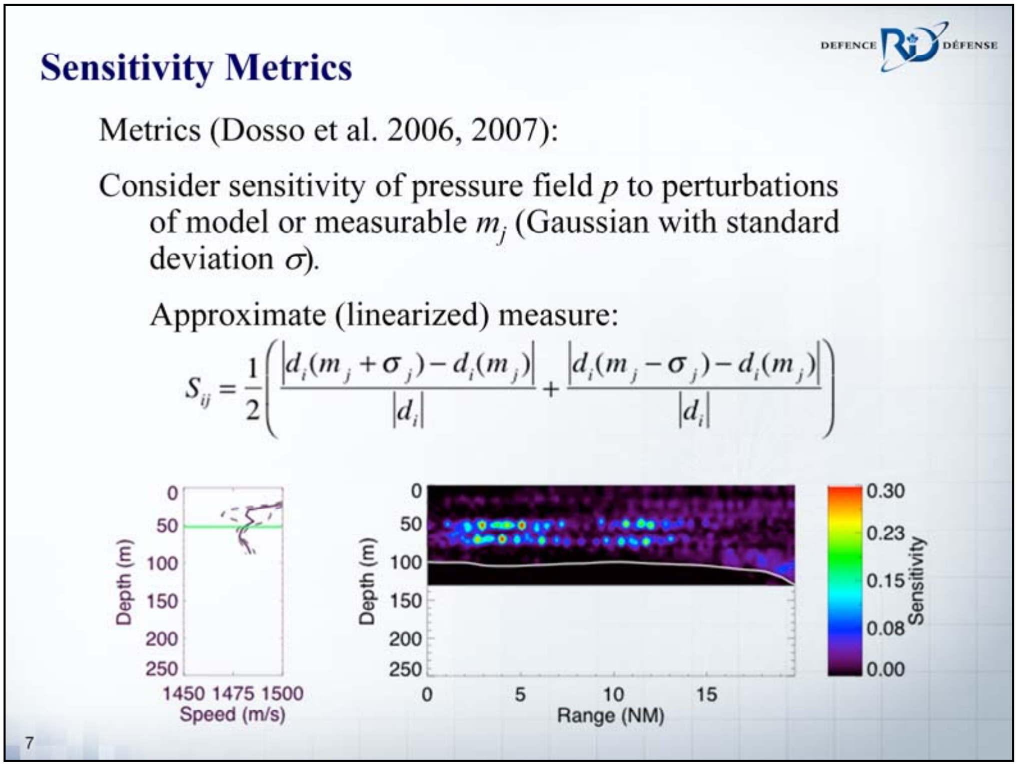
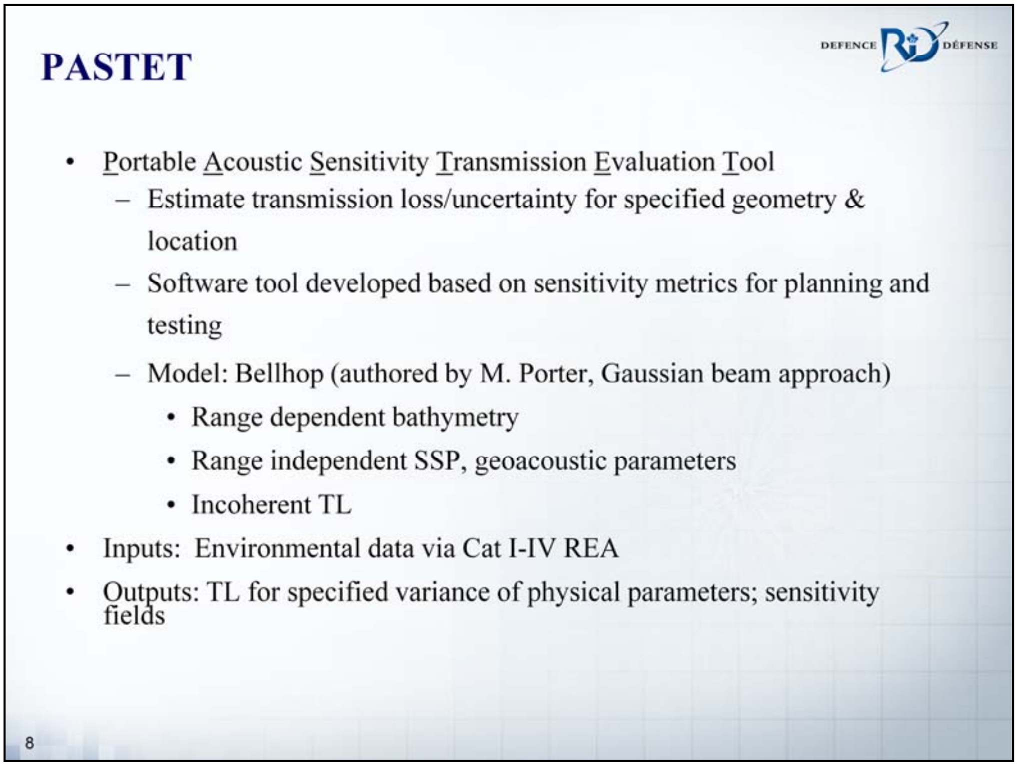
The method we use to measure sensitivity, i.e. to answer these questions, was developed in conjunction with Stan Dosso et al. (JASA, 2006 & 2007)

Basically, Monte Carlo sampling is used to draw random model perturbations δMj from a Gaussian distribution based on measured geoacoustic and oceanographic parameters, and a forward propagation model is used to compute the corresponding data perturbation (in this case, the perturbed pressure field) for each sample. The sensitivity is then the normalized RMS ensemble-averaged perturbation for each point of the pressure field relative to each model parameter.



An approximate linearized two-poing sensitivity measure can also be defined.

Output is a field showing sensitivity of pressure field to perturbations – in this case, the sound speed profile. Plot on the left shows mean and perturbed sound speed profiles, with the receiver depth shown in green. Plot on the right shows bathymetry as a white line, and range and depth dependent sensitivity – red is more sensitive, purple less.



Software tool developed for this

What dominates the uncertainty - parameter variance or lack of information about a parameter?

How to we choose a sampling strategy?

Surface loss calculated using Beckmann-Spezzichino model based on wind speed

Bottom reflection loss calculated from two-fluid layer model

Run in Incoherent TL mode

Field trial (Q325)

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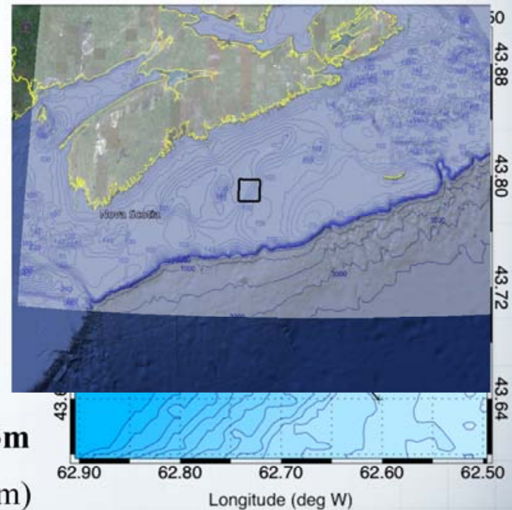
- October-November 2009
- Environmental data
  - Category I, II, IV
- TL runs
  - Frequency **1200**/3000 Hz
  - 2 sets of receivers
    - Depths **52m**, 72m
    - Water depth 248m, **143m**
  - Towed transmitter (75-90 m)



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Full set of measurements taken to make comparisons between different REA categories and to compare to measured TL data. (*click for zoom in on map*)

This area was selected because it had fairly benign oceanography, but varying bottom properties.

Category I REA

- Environment databases

	Category I	Category II	Category IV
Bathymetry	**ETOPO2**	High-resolution (Canadian Hydrographic Survey)	Single- or multi-beam bathymetry
Oceanography	**World Ocean Atlas (monthly climatology)**	Ocean forecast models (assimilation)	In-situ Moving Vessel Profiler, XBTs
Geoacoustic	**DECK41**	Empirical model based on bathymetry	FFCPT

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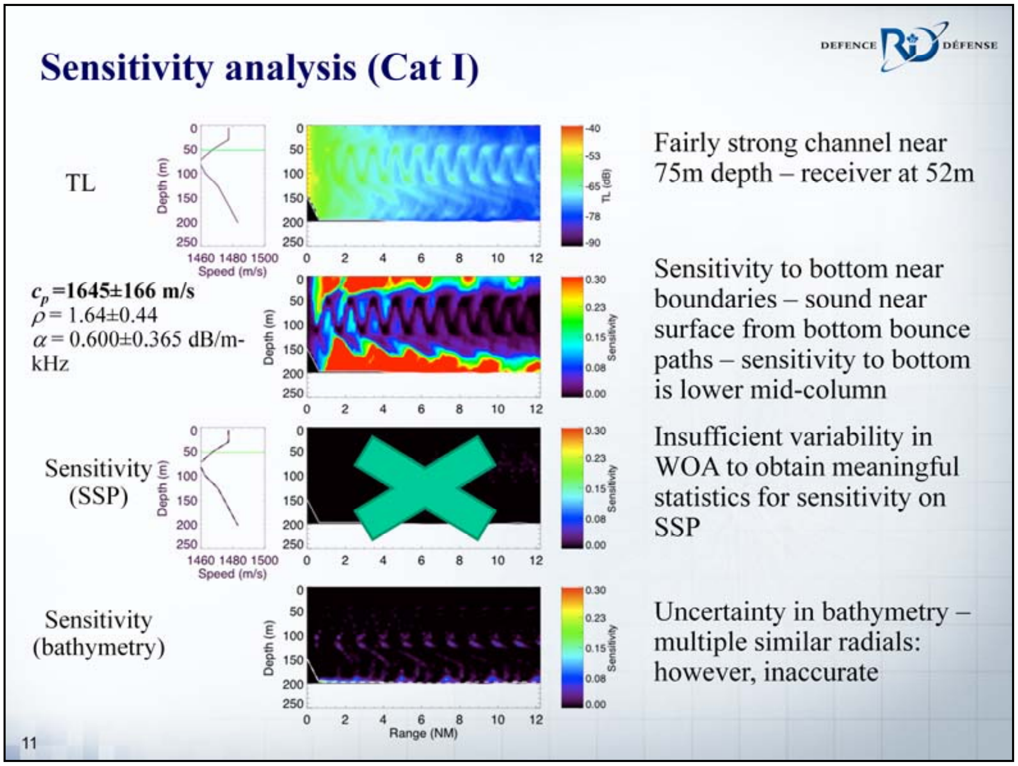
ETOPO2 bathymetry

World Ocean Atlas monthly climatology

DECK41 sediment database – gives sediment names (descriptions) (gridded, but sparse)

> Translated to grain size, thence to c_p, ρ, α. Neglect sediment thickness – unavailable in this DB, but in general the sediment is quite thick in the area, so not of as much concern due to frequency – the sensitivities to the first layer are orders of magnitude higher than to the basement



Environmental parameters and uncertainties are shown on the left, together with the receiver depth; here, we are looking at the receiver at 52 m water depth

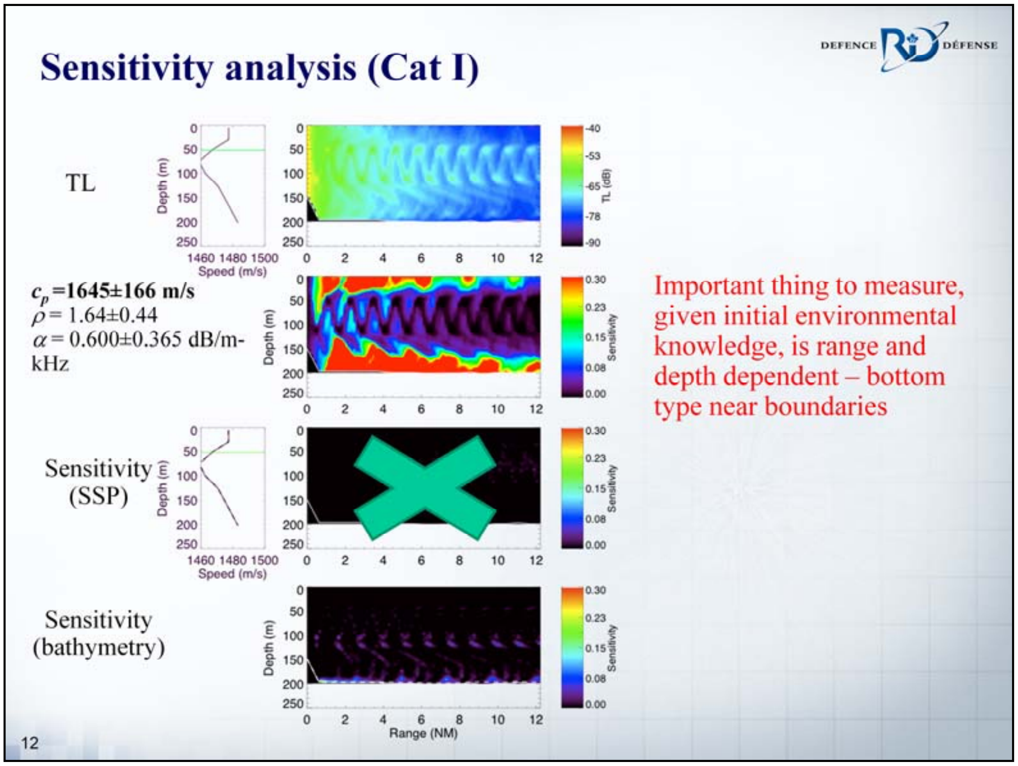
The transmission loss field is shown in dB of transmission loss. It is based on the mean input parameters *click* strong channel near 75 m water depth.

The bottom parameters have high uncertainties associated with them; in this experiment, the sensitivity to the bottom is primarily driven by sensitivity to the compressional sound speed, so that is used to indicate where the sensitivities to geoacoustic parameters lie and how large they are relative to the other environmental data.

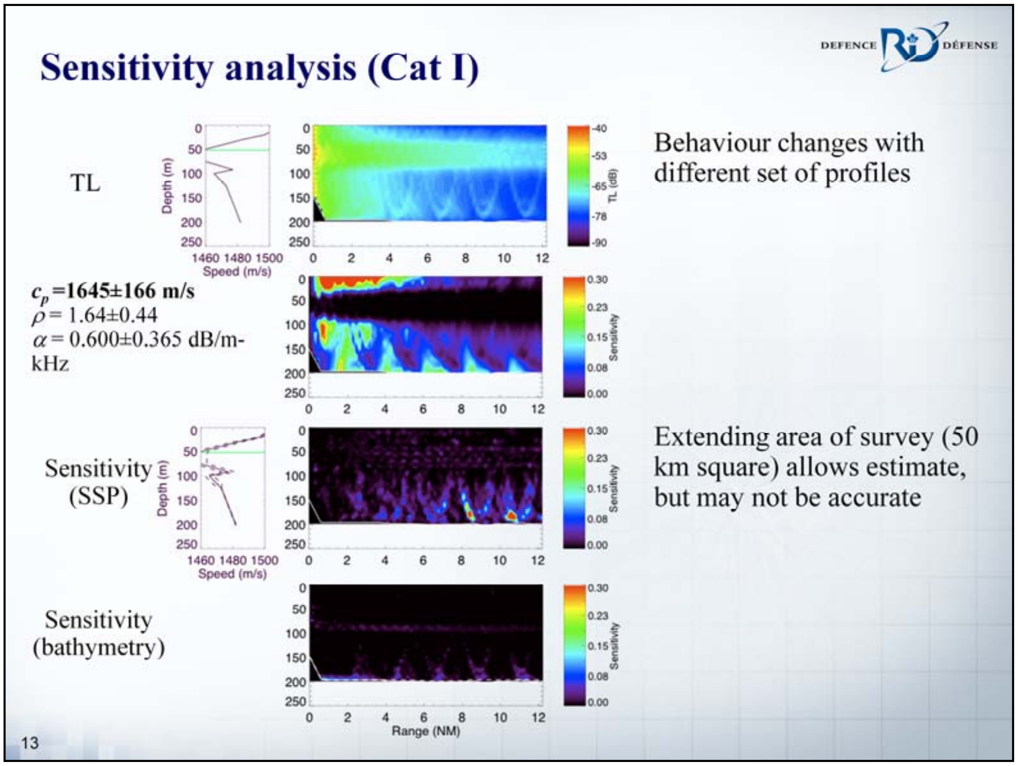
Note that as the transmitter moves in range and depth, the sensitivity to differing parameters varies greatly – in particular, if you have a hull-mounted sonar as opposed to a VDS, in this case, you are going to really need to know what is happening in the bottom.

Insufficient variability in WOA to obtain meaningful statistics for sensitivity on SSP

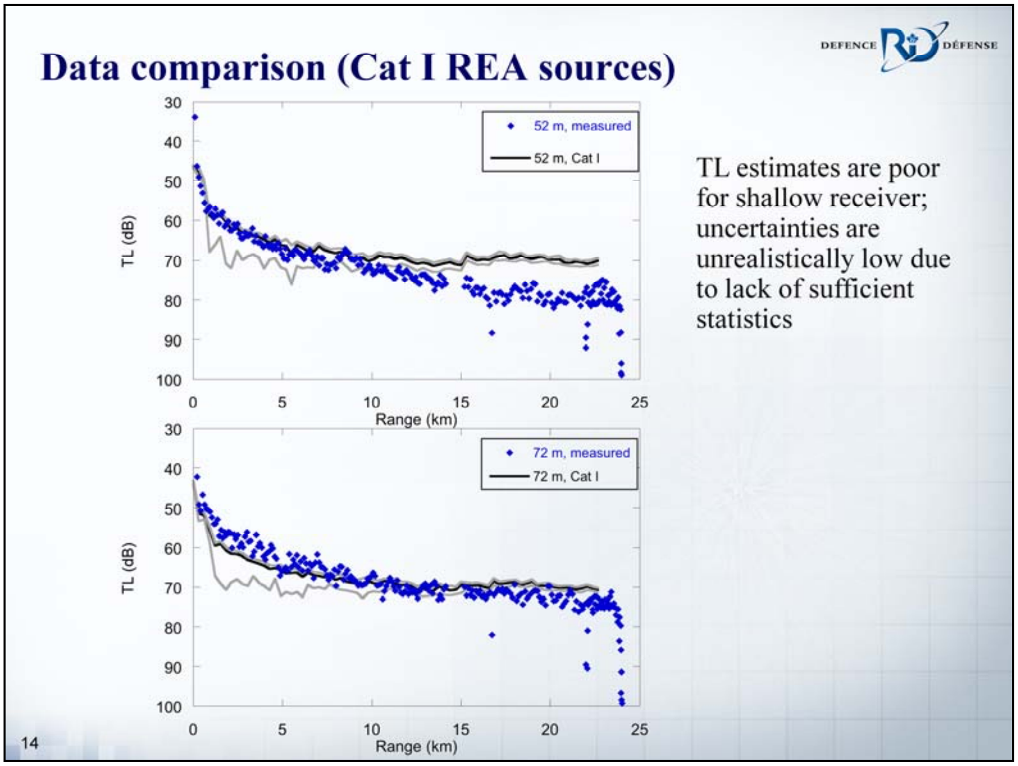
Sensitivity to bathymetry here shows evidence of ‘field shifting’ effects of environmental perturbation. Specifically, sensitivity will be high near the boundaries of the long-range propagation path, indicating that the path has shifted slightly in space due to the environmental perturbation.



Segue – what can we do to compensate for SSPs?



Given that we have insufficient statistics for meaningful water column dependence, we can extend the range over which profiles are taken includes other water masses, allows estimate of uncertainty on SSP, but develops possibly unrealistic profile behaviour. The change in behaviour of the TL field and on the sensitivity to the bottom indicates that the parameters all interact – some environmental knowledge is always required to get meaningful results.



In addition to range and depth dependent fields showing how the propagation depends on the various environmental parameters, the transmission loss based on the mean environment and the transmission loss envelope generated by the perturbations in the model parameters are computed. Here these (shown in black, with the envelope shown in grey), are compared to incoherent transmission loss measured on the upslope receiver at 52 m and 72 m depths (energy from 1100-1300 Hz LFM). Although we obtain a rough estimate of transmission loss, the loss is underestimated by the model by up to 10 dB at longer ranges for the shallow receiver. In addition, the uncertainties on the loss propagated from the uncertainties on the Category I REA data are unrealistically low at these depths due to the lack of reasonable uncertainty measurements for the SSP.

Category II REA

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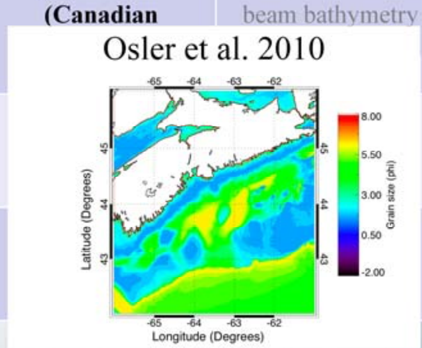
- Advance force/forecast

	Category I	Category II	Category IV
Bathymetry	ETOPO2	**High-resolution (Canadian**	Single- or multi-beam bathymetry
Oceanography	World Ocean Atlas (monthly climatology)		
Geoacoustic	DECK41		



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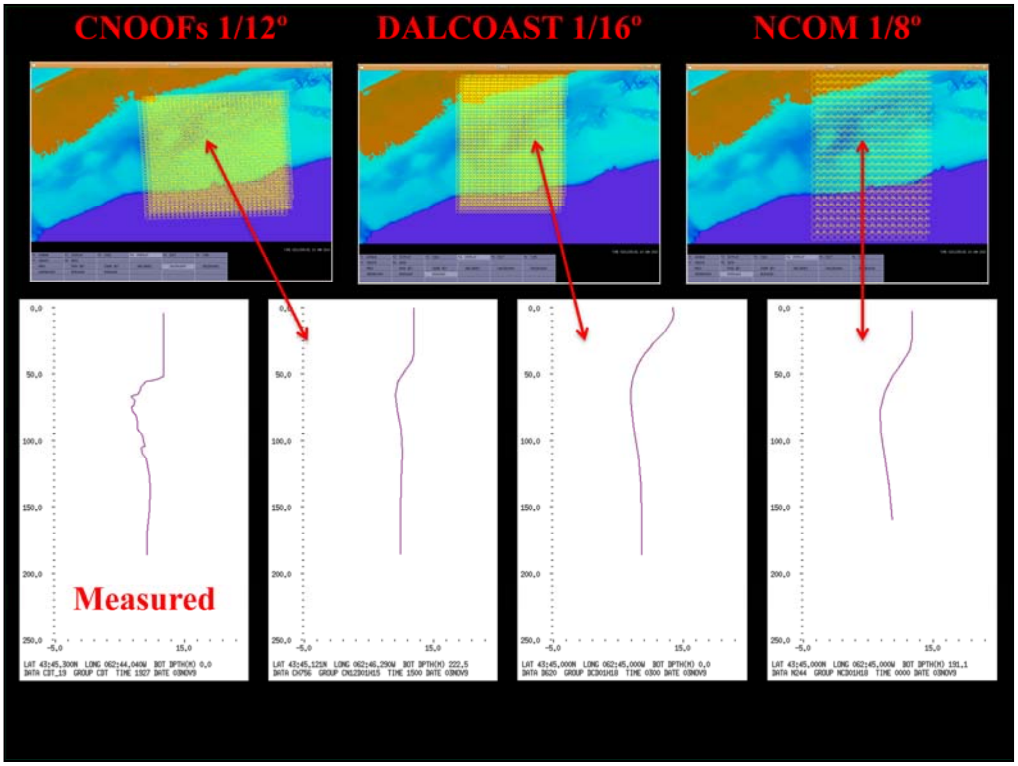
Empirical model, which calculates mean surface grain size based on bathymetry for the Scotian Shelf area, as discussed by John Osler on Friday

I'll give an overview of the ocean forecast models used for this (here used without assimilation of XBTs – in other Cat II scenarios, satellite SSTs or dropped XBT fields could potentially be assimilated)



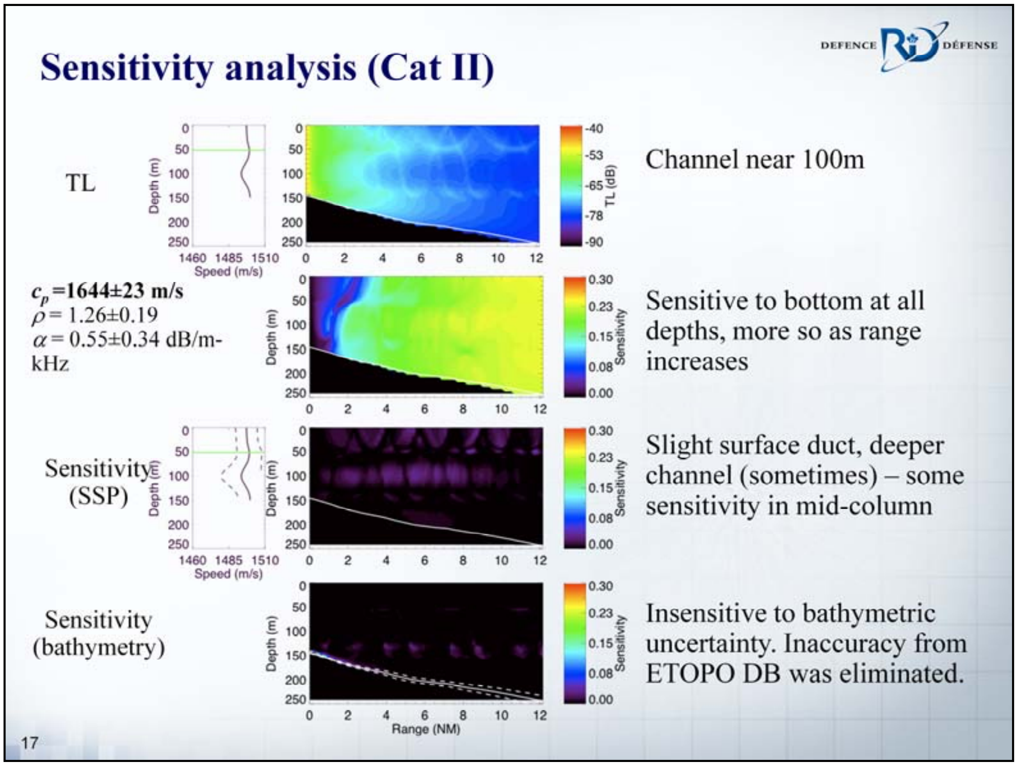
Sound speed profiles (SSPs) from numerical models of oceanographic conditions

- C-NOOFS (Canada-Newfoundland Operational Ocean Forecasting System) from DFO. – uses global Mercator model for boundary conditions
- DALCOAST III from Dalhousie University
- Global NCOM (Navy Coastal Ocean Model) from U.S. Naval Research Laboratory 1/8º,
- Which provides 50 vertical levels

Attributes:

- All provide forecasts/nowcasts of conditions
- Differ in their spatial resolutions, assimilation capabilities, and wind and tidal forcings.

- Pseudo-assimilation: best appearance for the previous TL run (November 3) was from CNOOFS model, so that was selected – the profiles from this were used for the next phase
- This, along with the high resolution bathymetry and the empirical grain size model, was used for the input to the PASTET tool to look at sensitivity to uncertainties in Cat II REA environmental data



Environmental parameters and uncertainties are shown on the left, together with the receiver depth; here, we are looking at the receiver at 52 m water depth

The transmission loss field is shown in dB of transmission loss.

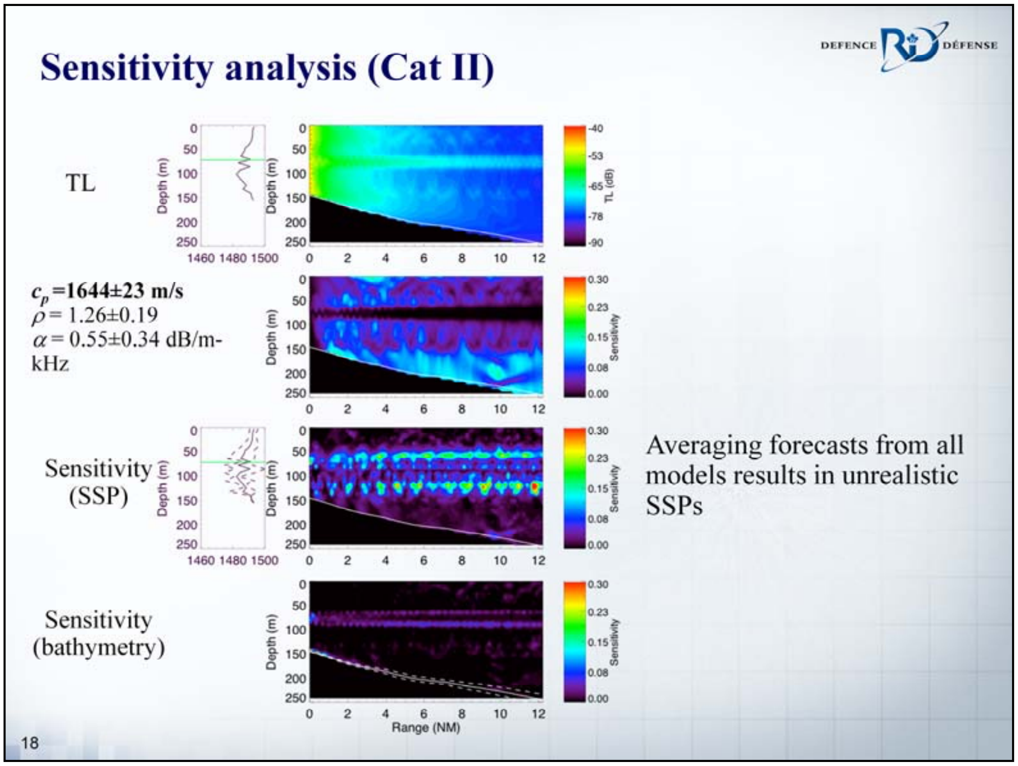
The bottom parameters are better constrained, and in fact within the uncertainties for the parameters as found in the Category I.

Sensitivity to sediment sound speed is generally lower than sensitivity to the other two parameters. It generally increases with range, indicating that the effect of the sediment sound speed change on transmission loss is cumulative in some sense.

The sound speed distribution, based on the values from the CNOOFS model, is actually more or less bi-modal. Interestingly, an average can be made using SSPs from all model forecasts, but this gives unphysical results. An open question is how to best represent the variability in the sound speed profiles while keeping the required “shapes”. One possibility is to perform multiple model runs and use the model outputs as the distribution from which to select sound speed profiles.

Sensitivity to all parameters is generally low when propagation is dominated by in-channel propagation. This is especially true within the channel.

Sensitivity to bathymetry and sound speed profile often shows evidence of ‘field shifting’ effects of environmental perturbation. Specifically, sensitivity will be high near the boundaries of the long-range propagation path, indicating that the path has shifted slightly in space due to the environmental perturbation.



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The sound speed distribution, based on the values from the CNOOFS model, is actually more or less bi-modal. Interestingly, an ensemble average can be made using SSPs from all model forecasts, but this gives unphysical results. A question is how to best represent the variability in the sound speed profiles while keeping the required “shapes”. Hopefully, we can use some of the techniques for super-ensemble averaging described on Tuesday to explore this question, and to compare results using each model individually with those from a set of different models.

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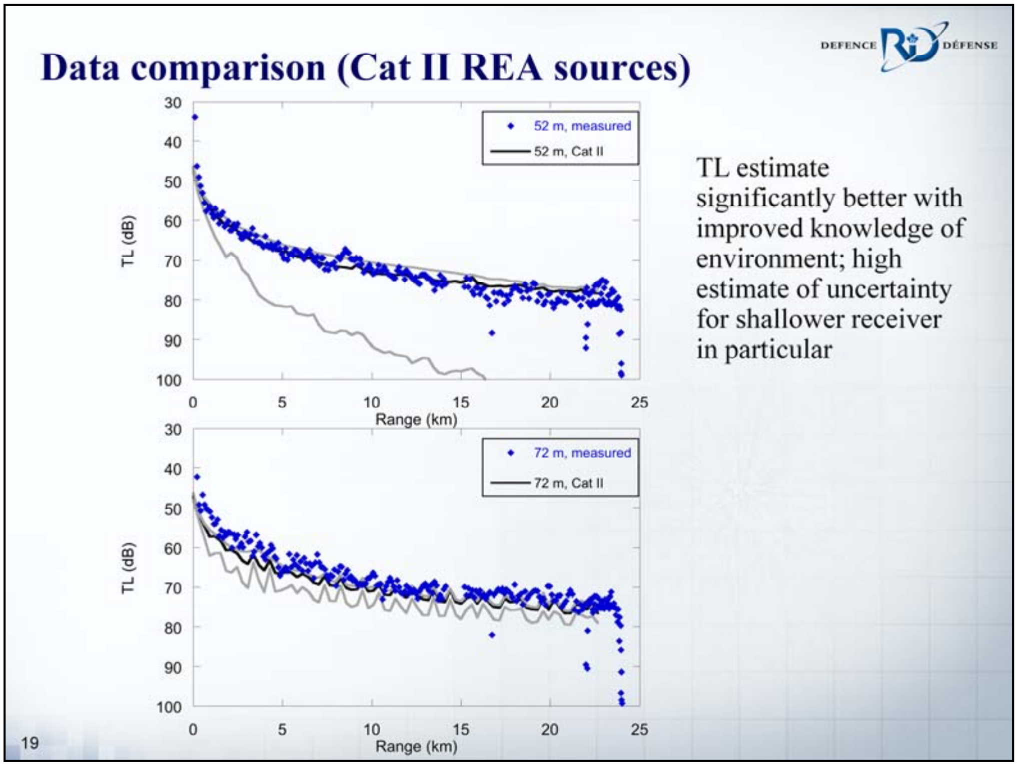
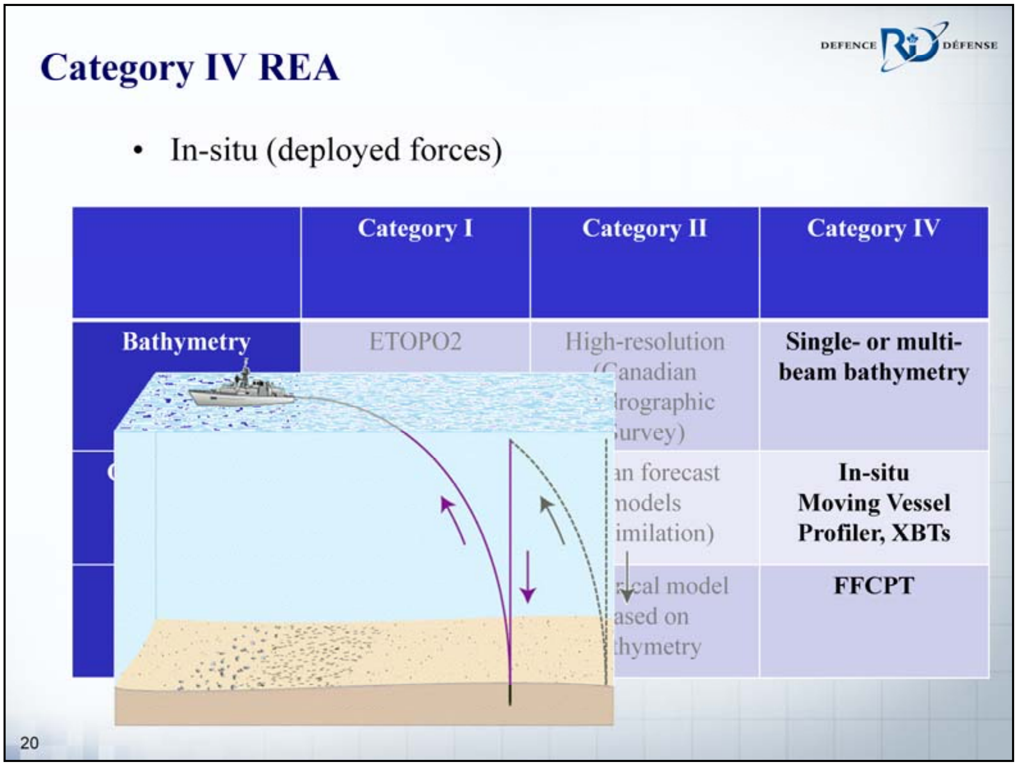


The envelope of likely transmission loss tends to include most of the measured points, but the potential uncertainty on the shallow receiver in particular is very high – in particular, based on



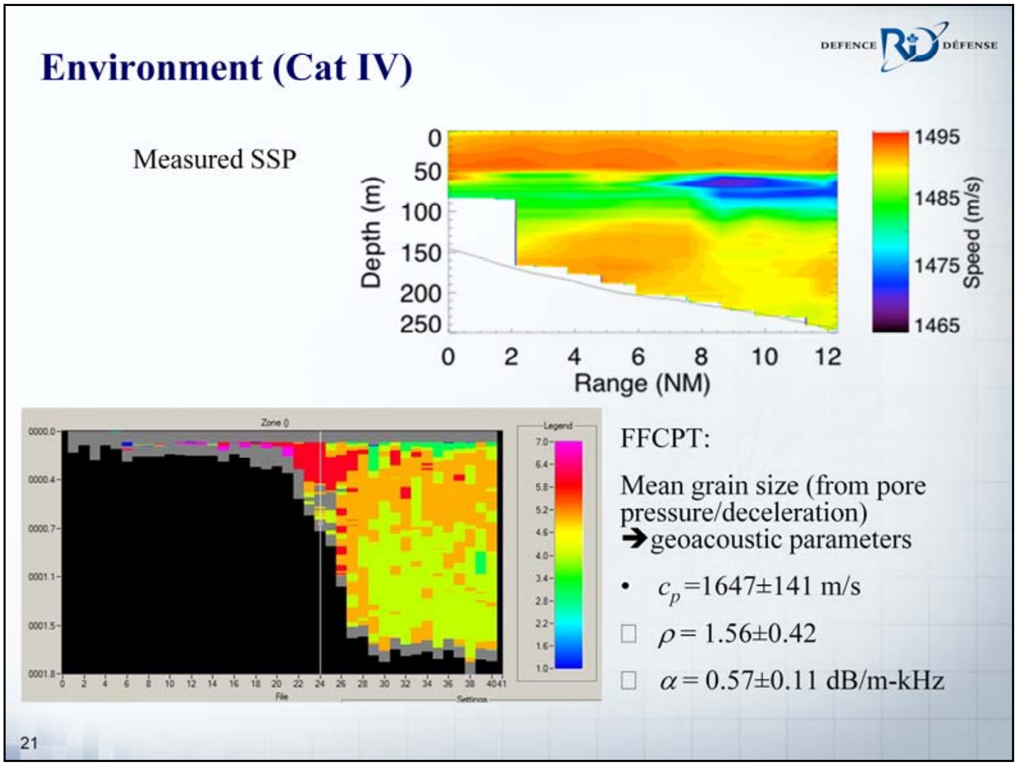
In-situ data

Bathymetry: single or multi-beam systems on-scene

Sound speed profile: Moving vessel profiler and XBTs

Geo-acoustic parameters: Free-falling cone penetrometer (grain size)

Sediment thickness: Sub-bottom profiler (neglected in this case)

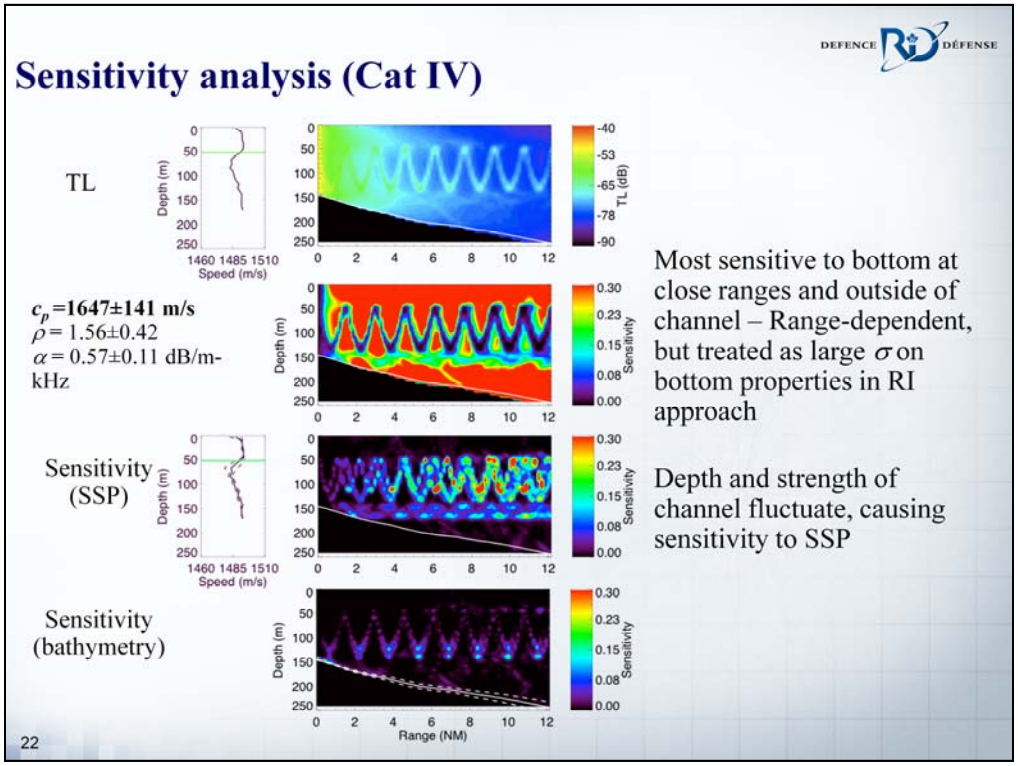


APL-UW Environmental handbook

SSPs measured using combination of XBTs, XSVs

FFCPt shows that in the deeper portions of the basin, the sediment is softer (as predicted using the model)

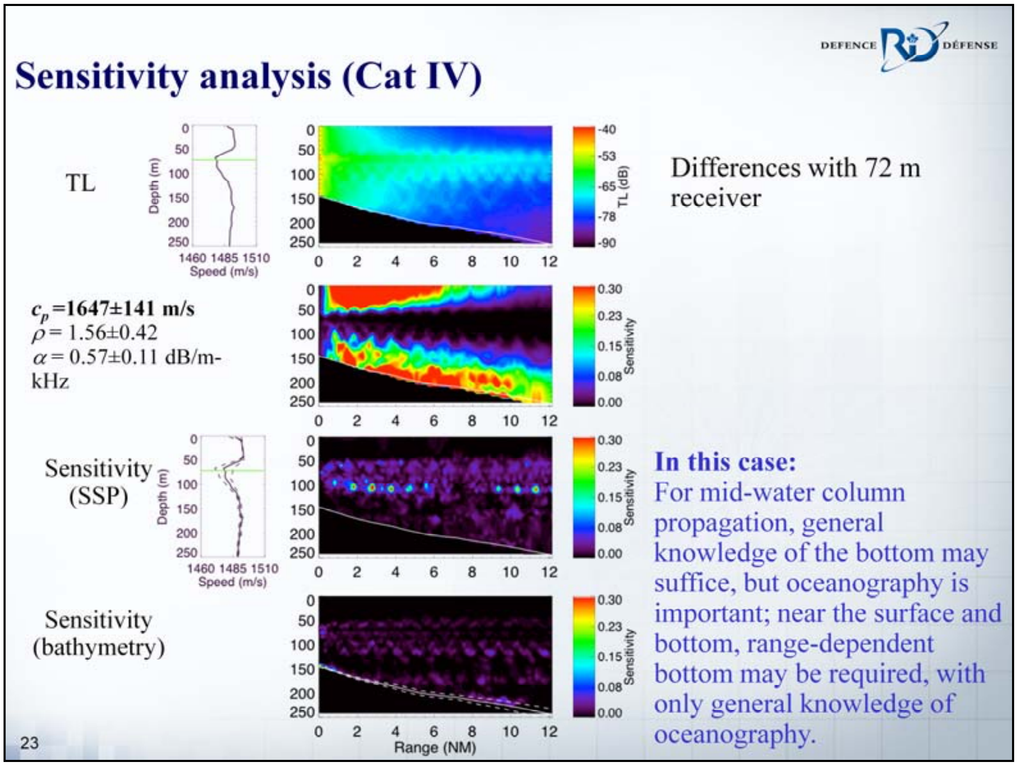
Both SSP and sediment properties are actually range-dependent, but we are computing uncertainties and assuming range-independence.



Sensitivity to sediment sound speed is generally higher than sensitivity to the other two parameters, except in the channel. This may be due to the poor constraints on it. It is particularly high near the surface at close ranges, where the only paths are bottom-bounce.

Sensitivity sound speed profile is highest for in-channel propagation.

For mid-water column propagation, general knowledge of the bottom with more knowledge of the oceanography should suffice; near the surface and bottom, range-dependent bottom may be required, again with only a few measurements of SSP.



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Sensitivity sound speed profile is highest for in-channel propagation.

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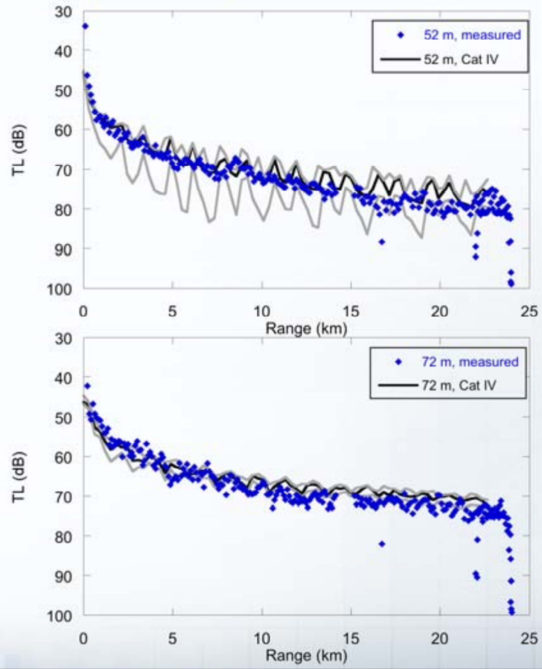
Data comparison (Cat IV REA sources)



Larger uncertainties for shallow receiver due to “uncertainties” regarding bottom and water column (variability), but good agreement with measured TL – does not evidence much improvement over Cat II

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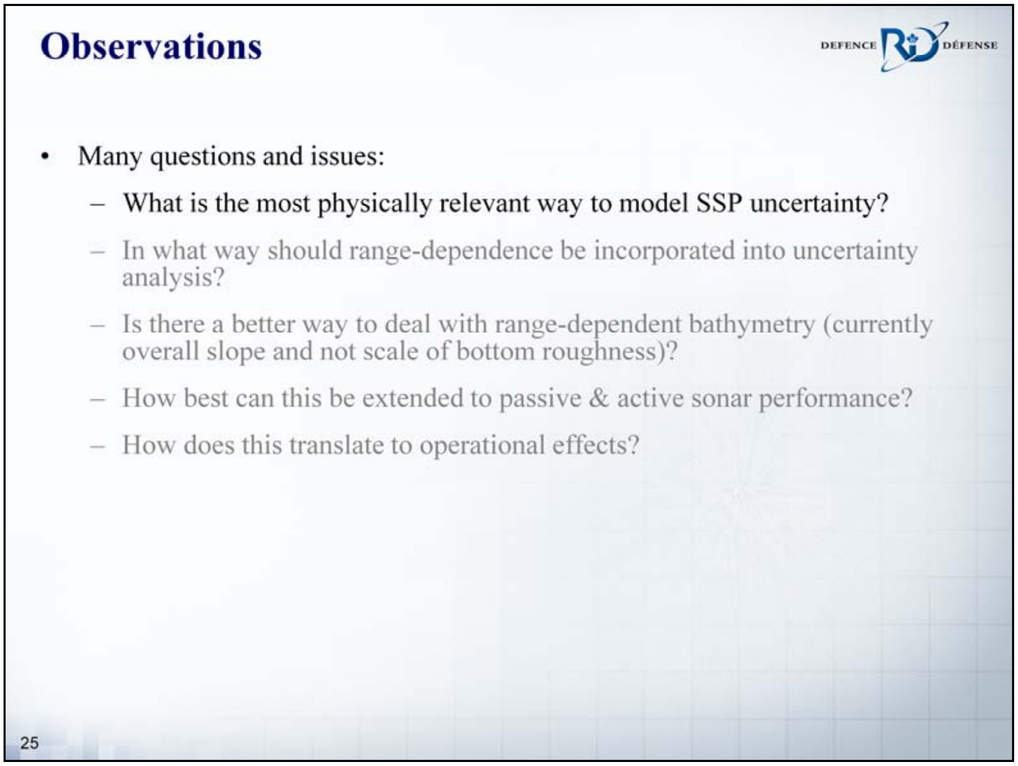
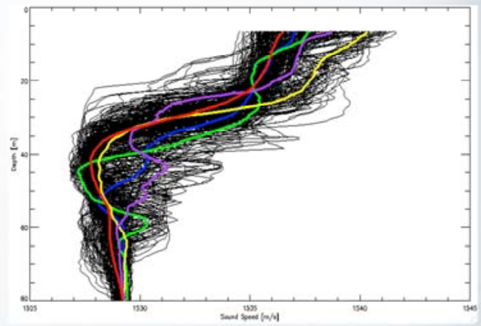


Manypossibilitieshavebeendiscusseddduringthisconference. EOFs, or using e.g. The super-ensemble techniques for forecast SSPs

Oceanographic uncertainies

- Sound speed profiles
  - Ensemble average, point-by-point
  - Thinning, selection of points
  - Clustering techniques
  - EOFs



- Model forecasts
  - Model ensembles and super-ensemble techniques

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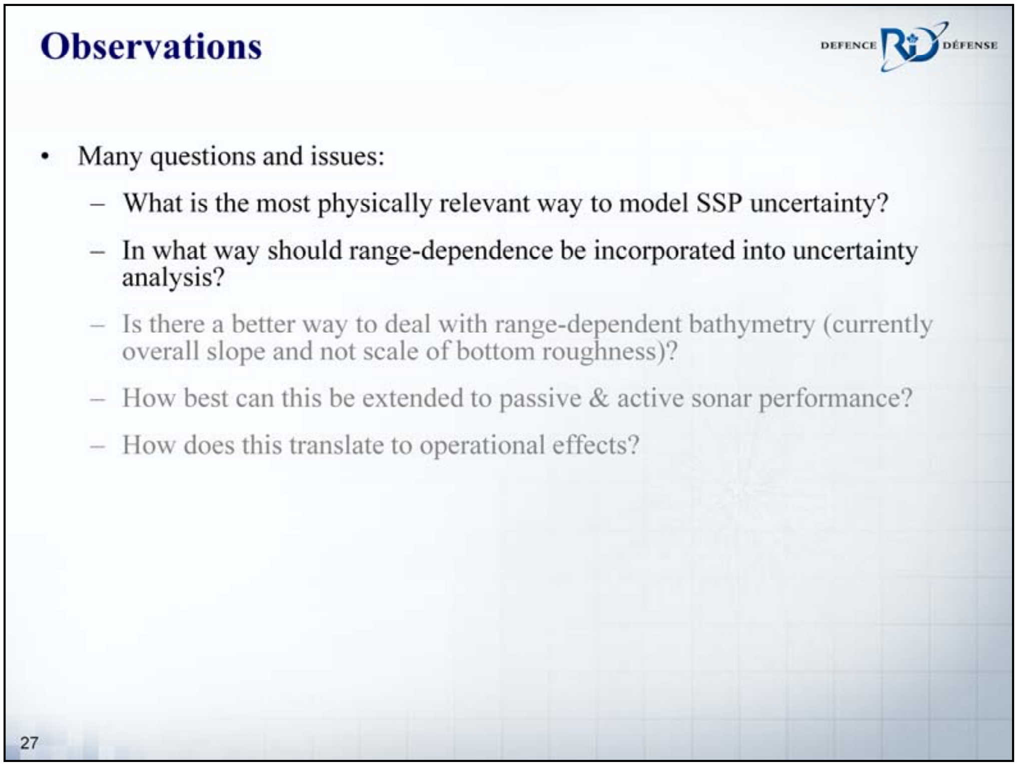

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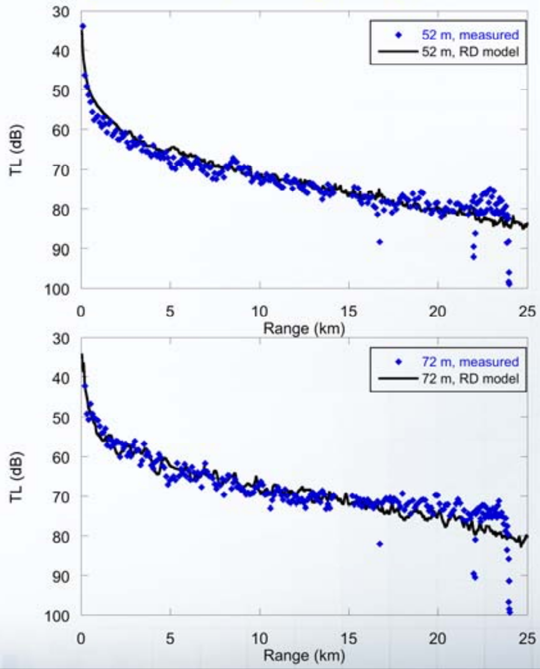
Data comparison (Range-dependent model)



Range-dependent model w/o uncertainties shows excellent fit, but may not always be possible (or necessary)

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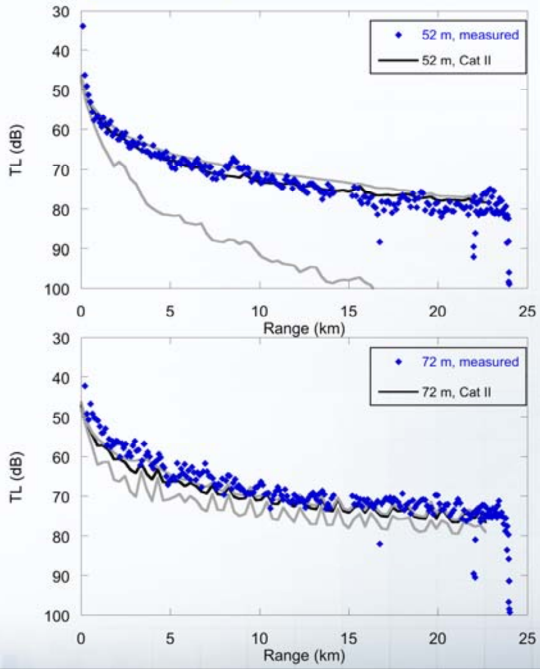
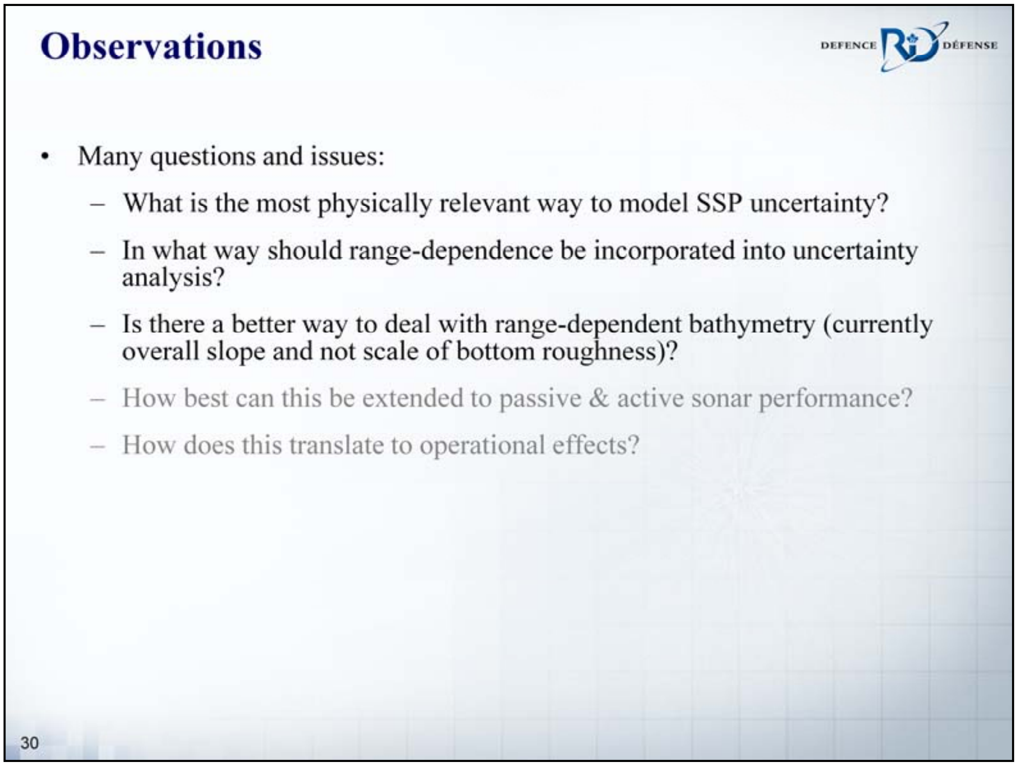
Data comparison (Cat II REA sources)



How much accuracy is enough?



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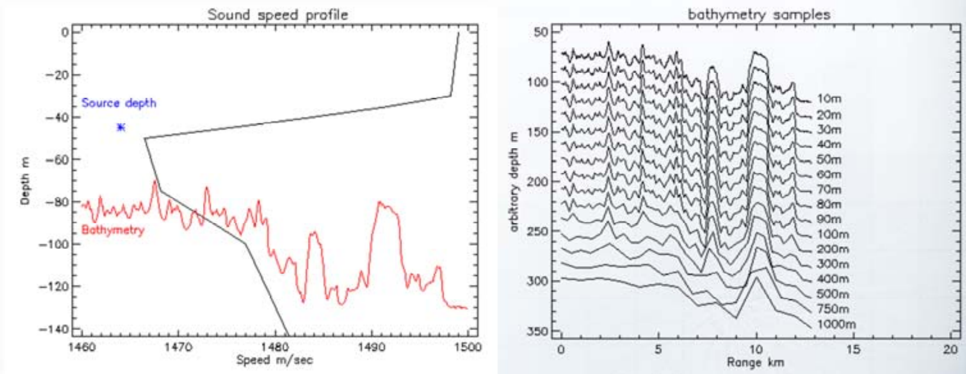
Effects of Bathymetric Resolution:

ΔTL (dB) in field relative to 10 m bathymetry



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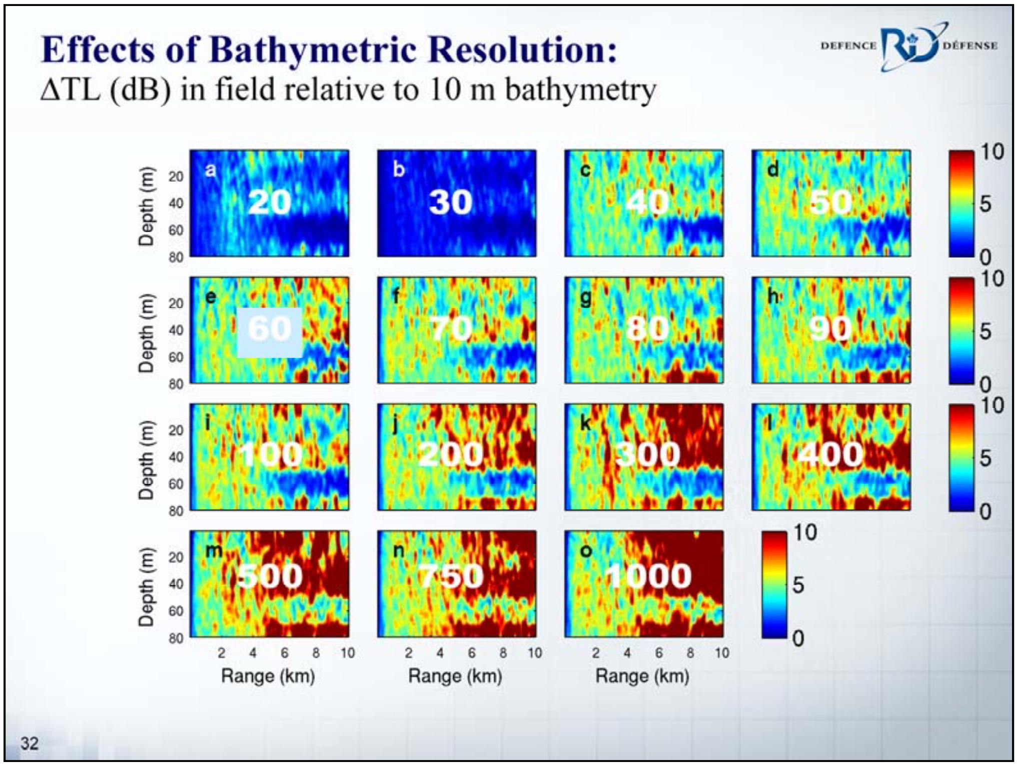
Sensitivities to water column depth and sound speed are nonlinear and large

Range and depth dependence of sensitivity to water column properties is determined by the structure of the acoustic channel. For example, using the unperturbed SSP, sound that is trapped in the subsurface channel is relatively insensitive to the water column depth.

There is significant fine-scale structure in the full-field sensitivity. This is probably due to the fact that perturbations to the water column properties change the details of the spatial distribution of the field. The pointwise sensitivity measure used in this study will detect these shifts as large changes in the pressure field.



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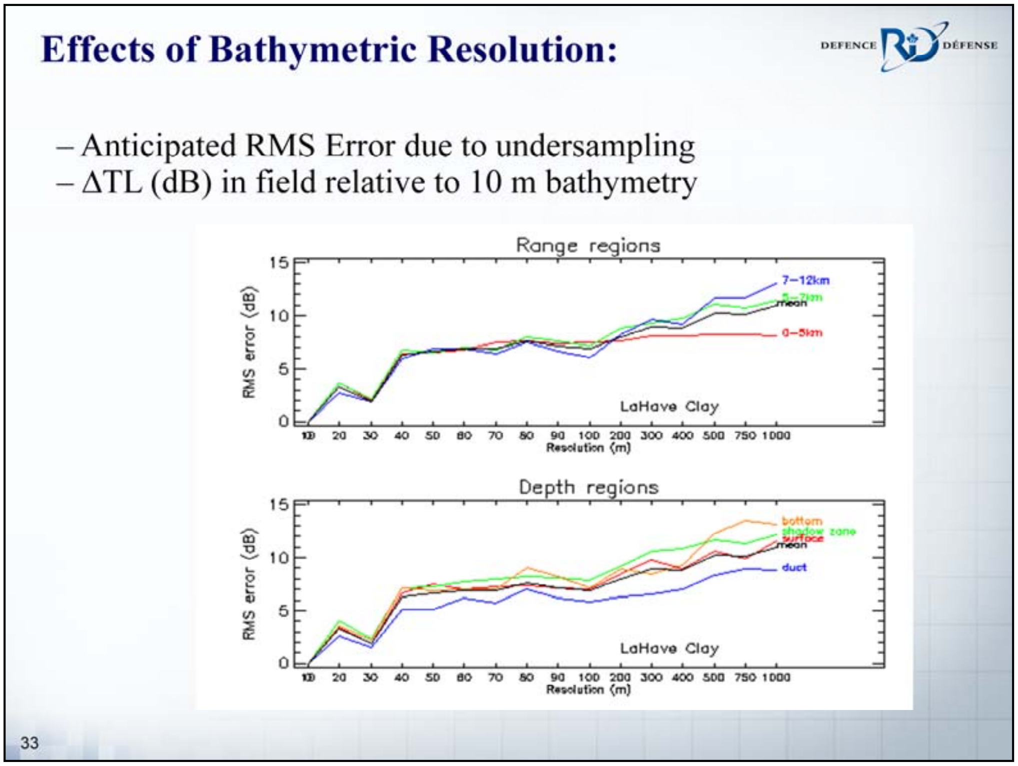

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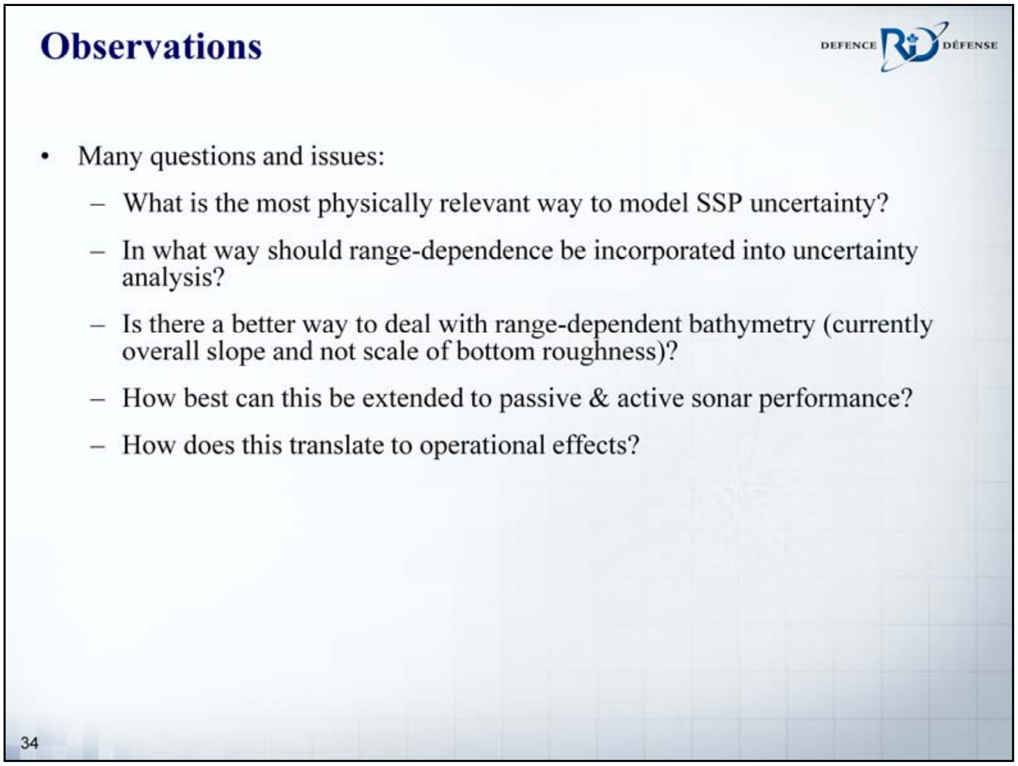

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Observations

- Illustrated method to determine most sensitive parameters for acoustic propagation in a given environment as a function of source and receiver geometry
- Important parameters and measurements required depend on environment, range, and depth
- What is sufficient?
  - Higher REA categories may not always provide most cost-effective solutions
  - Requirements-driven

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Typically trading dollars for decibels; higher REA categories will not always provide best bang for the buck.

Acknowledgements

- GD Canada
- MetOc Halifax
- Department of Fisheries and Oceans - Northwest Atlantic Fisheries Centre (NAFC)
- Naval Research Laboratory – Stennis
- Dalhousie University - Department of Oceanography
- Colleagues at DRDC Atlantic and DRDC Ottawa
- Spaceborne Ocean Intelligence Network and Canadian Space Agency
- Fred Campaigne

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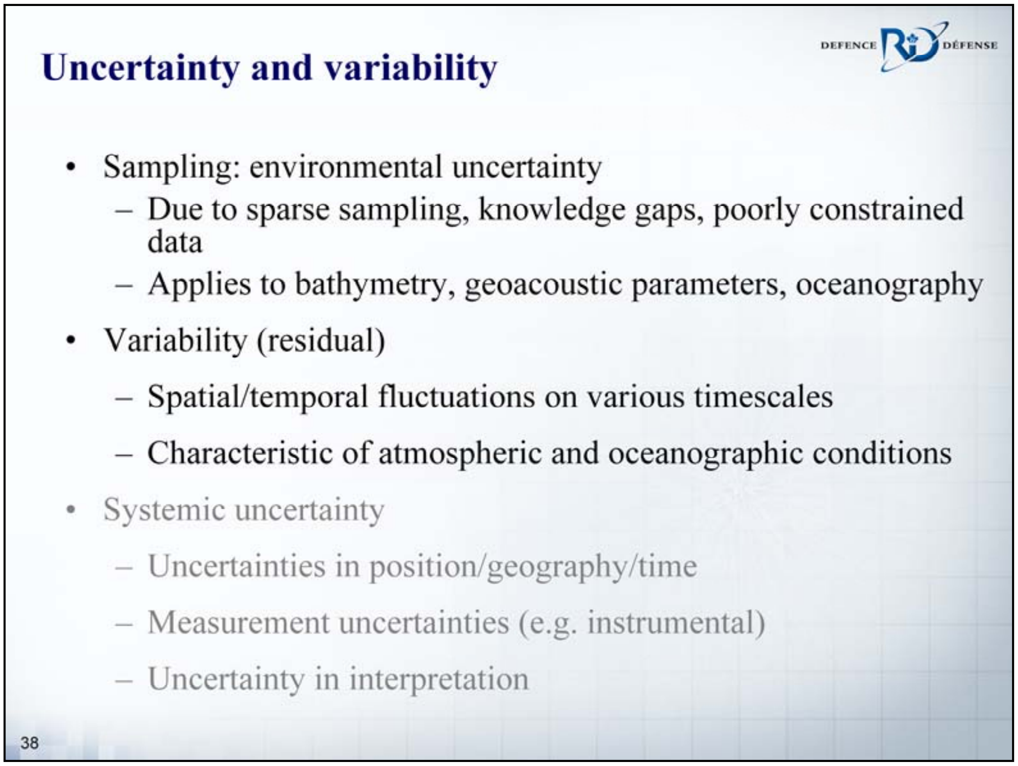


In order to determine what effect REA-based uncertainty has on acoustic propagation and sonar performance, we need to look at where the uncertainties lie

Sampling: environmental uncertainty

Due to sparse sampling, knowledge gaps, poorly constrained data

Applies to bathymetry, geoacoustic parameters, oceanography

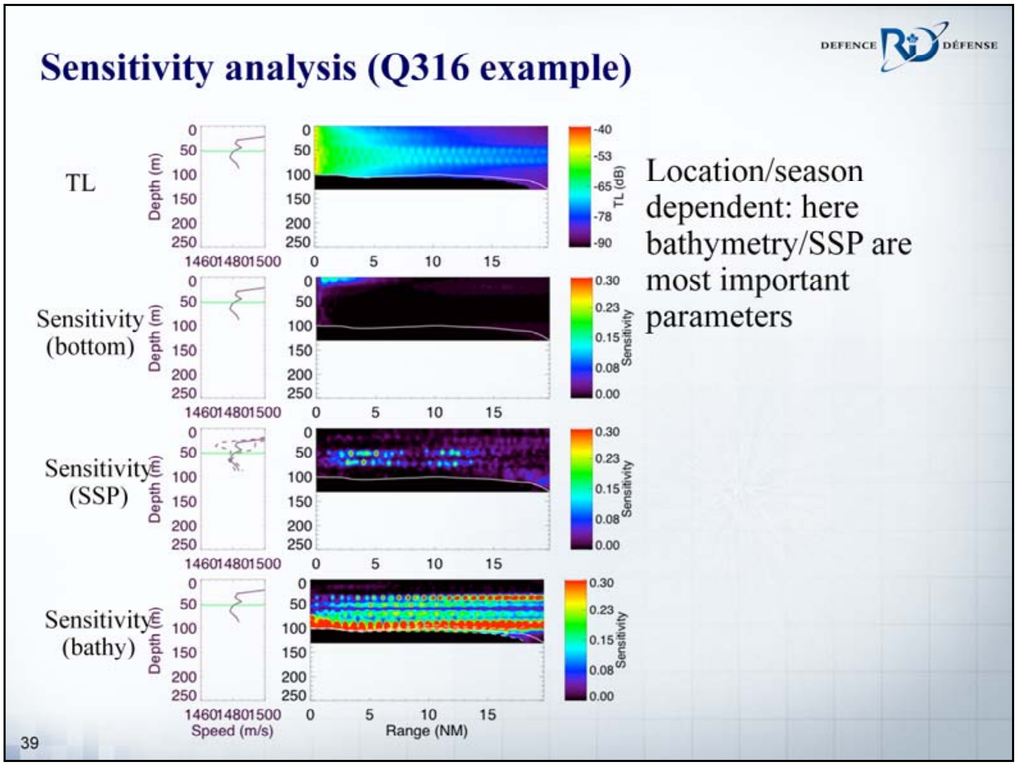
Variability (residual)

Spatial/temporal fluctuations on various timescales

Characteristic of atmospheric and oceanographic conditions

Further uncertainties follow through the remaining parts of performance prediction (*** explain more)

What approach do we take to coping with uncertainty?



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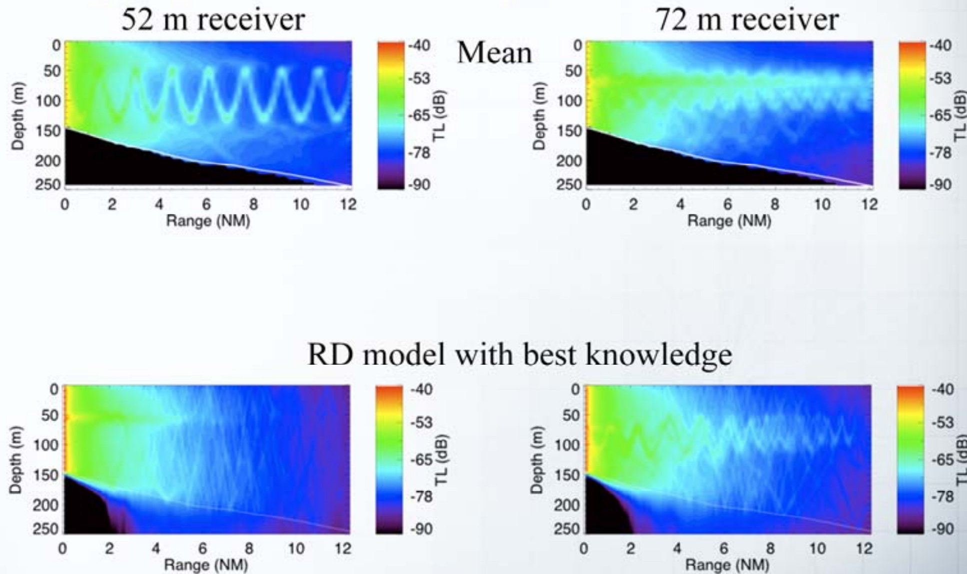
Range-dependent model comparison



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