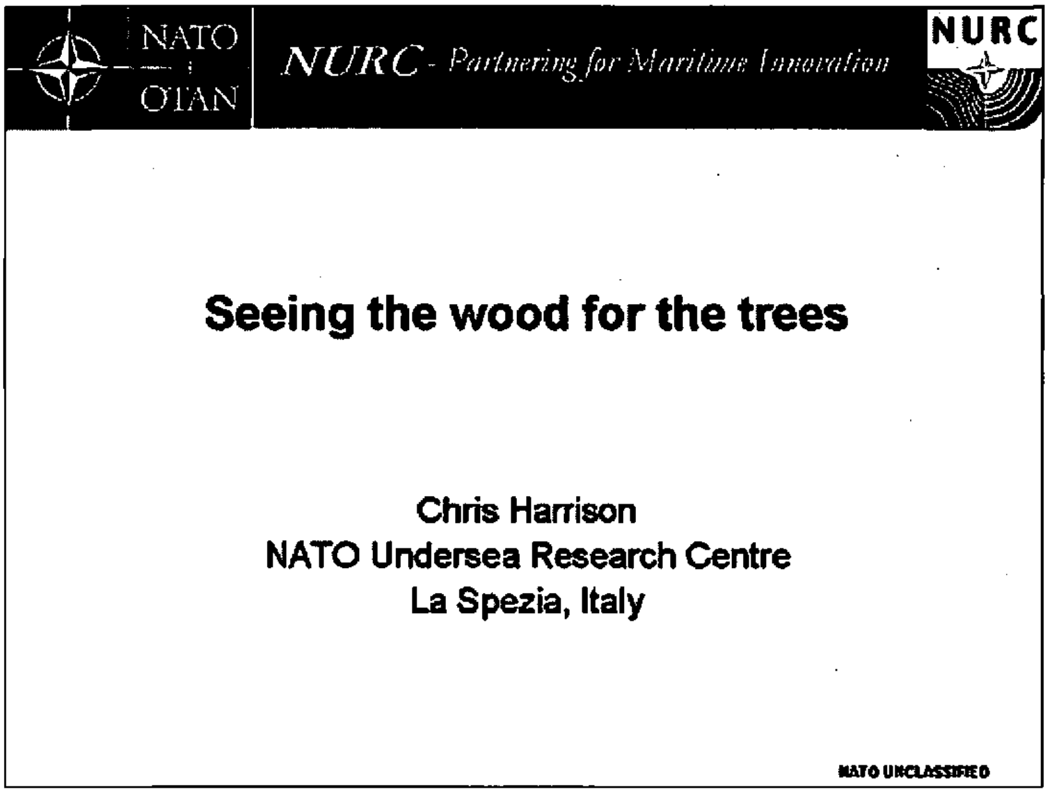
SEEING THE WOOD FOR THE TREES[1]

Chris Harrison, NATO Undersea Research Centre, La Spezia, Italy

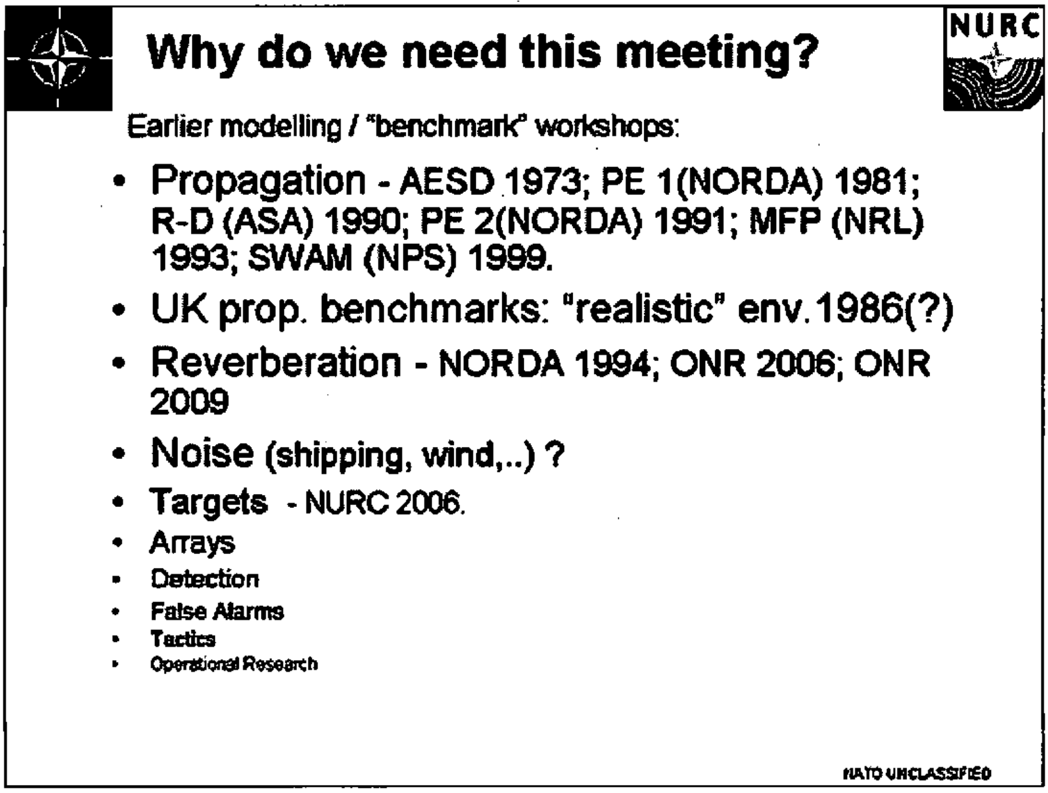


1 I'm honoured to be asked by Mike to give this talk. It's a great pleasure to be back in this institution – by pure coincidence Clare is my old college (I was here from 65 to 72 – I was a slow learner) – and there was no such thing as Lerner Court and neither was there a Forbes Mellon library – it was just grass. Also you had to go outside to find girls! Then you had to help them get round the gate posts and through the Master's Garden down by the river which you may have seen. Amongst the famous people who went to Clare are David Attenborough, Andrew Wiles (cracked Fermat's last theorem), Siegfried Sassoon (First World War poet). People like Sir Isaac Newton went somewhere down the road – don't know where!

It's also an honour to be opening this workshop on Sonar Performance. I'm sure it will be very stimulating and we will all go away feeling possibly:
- more confident
- more confused
- but at least we will have a lot of things to think about

Above all it's an honour to be opening the talks at this David Weston Memorial Sonar Performance Assessment Symposium. In a moment I'll say something about my claim to be standing here. First ....

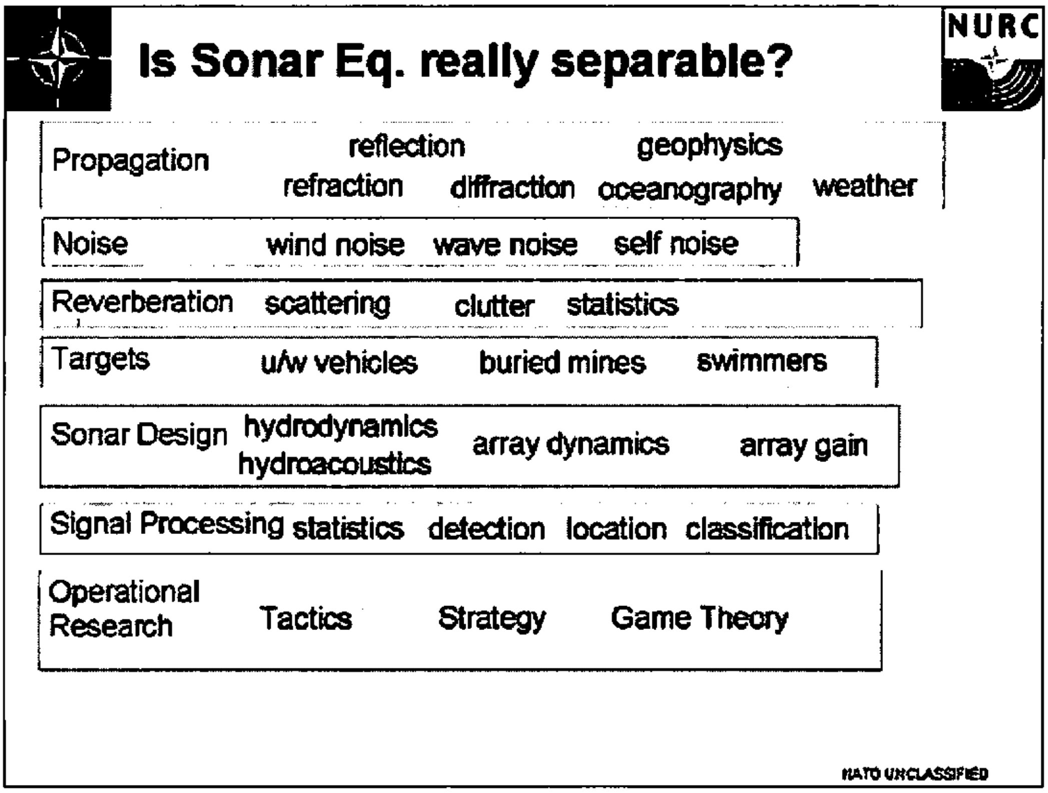
[1] Editor's note: Chris Harrison's keynote speech is reproduced in the proceedings unedited except for explanatory footnotes added by the editor. The title "Seeing the Wood for trees" was a favourite expression of David Weston, in whose memory the meeting was held.



2 Why do we need to worry about sonar performance or benchmarking sonar performance models? There've been many workshops about benchmarks, propagation, reverberation, and so on, in the past. But there hasn't been so much on the other bits and pieces, in particular, sonar performance modelling as a whole. That's because ....

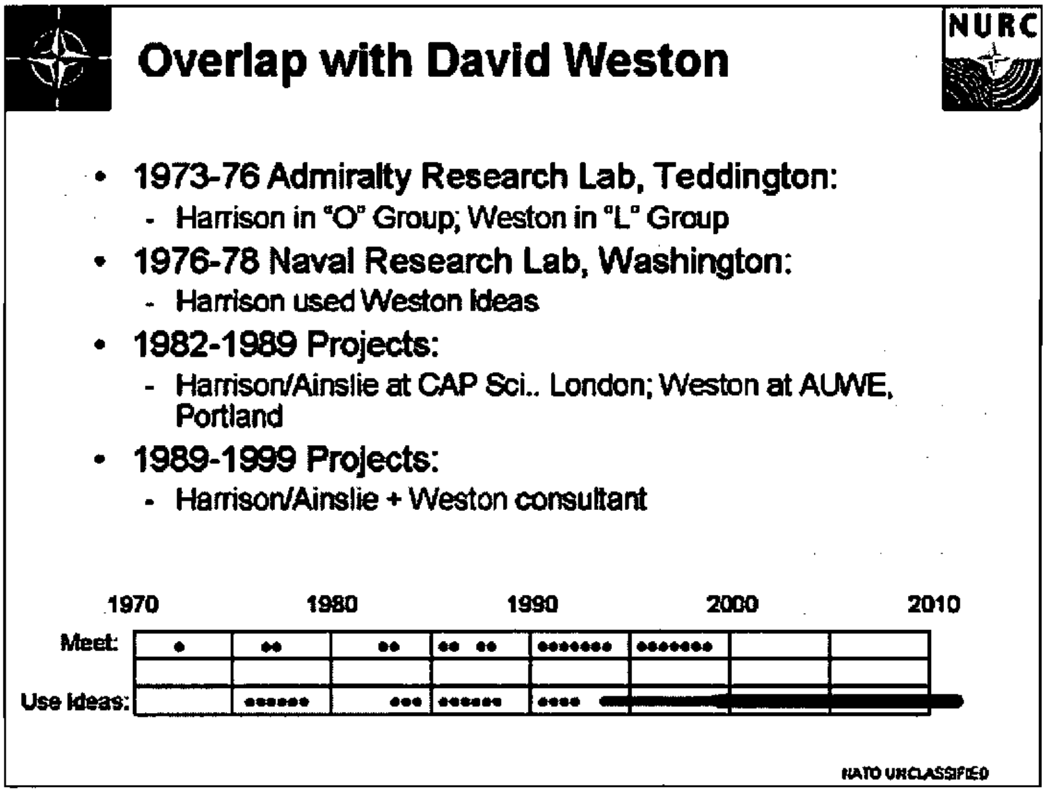
3 ... That's because it's an enormous subject! What I meant by "seeing wood for trees" in the title is this. Here's the forest – and we're trying to see what's going on.

4 ... This is what you have to take account of when you assess sonar performance. So it's a little bit more complicated.



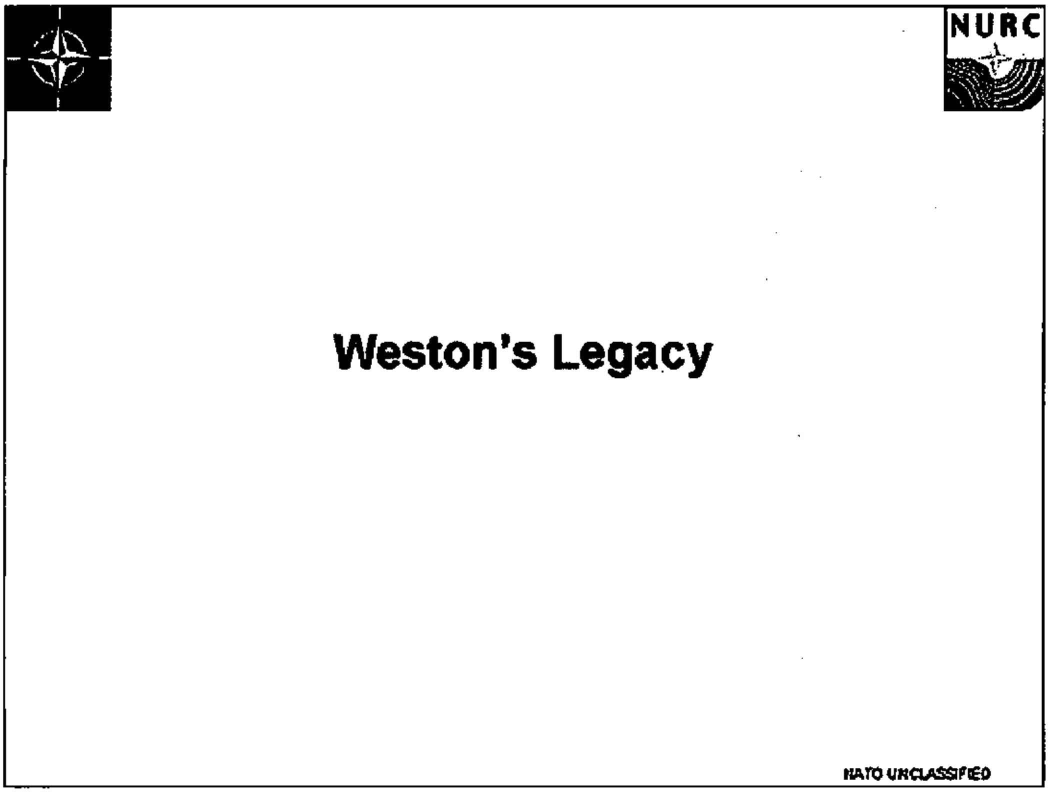
5 Also if you take the same subjects and put boxes round them you get the terms in the Sonar Equation and you also get the DEPARTMENTS that you typically find in research labs. In other words the discipline is strongly compartmentalised.

Well, are these things really separable? I'll come back to that, but you often get problems when you start putting these sonar terms together, and I think this stems from the fact that they aren't really separable.

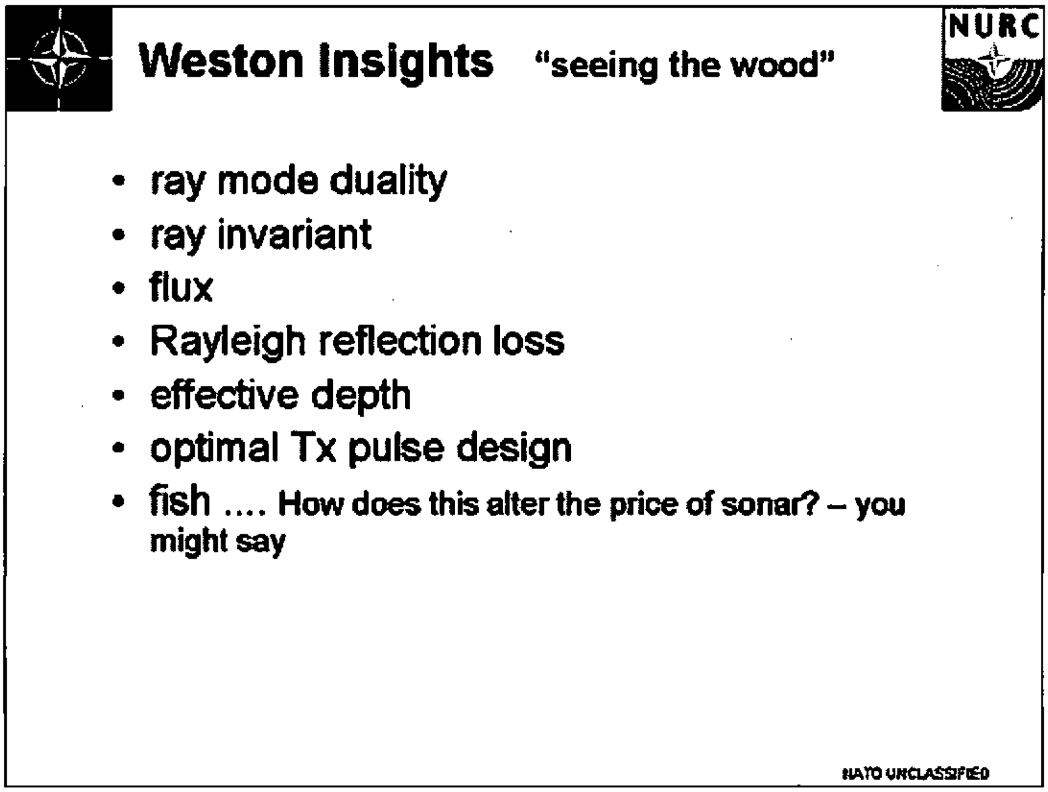


6 Before I go any further, perhaps I should say why I am standing here talking at this memorial to David Weston. Well I overlapped with him when I was in my first job at Admiralty Research Lab in Teddington. Then when I went NRL[2] I was working on some very long range bistatic reverberation in the Norwegian Sea and I started thinking about rays bending horizontally through reflecting at the seabed many times. It turned out that Weston had already done some work in this line (which I'll talk about in a minute). Then later on when I was in CAP Scientific/YARD/BAe there were a few projects on which Mike Ainslie and I worked while Weston was on the client side at AUWE[3], Portland. Finally we worked together much more closely, with Weston as a consultant, on various projects to do with sonar assessment and the UK Sonar Modelling Handbook.

[2] Editor's note: US Naval Research Laboratory, in Washington, D.C.
[3] Editor's note: UK Admiralty Underwater Weapons Establishment, in Portland, Dorset.

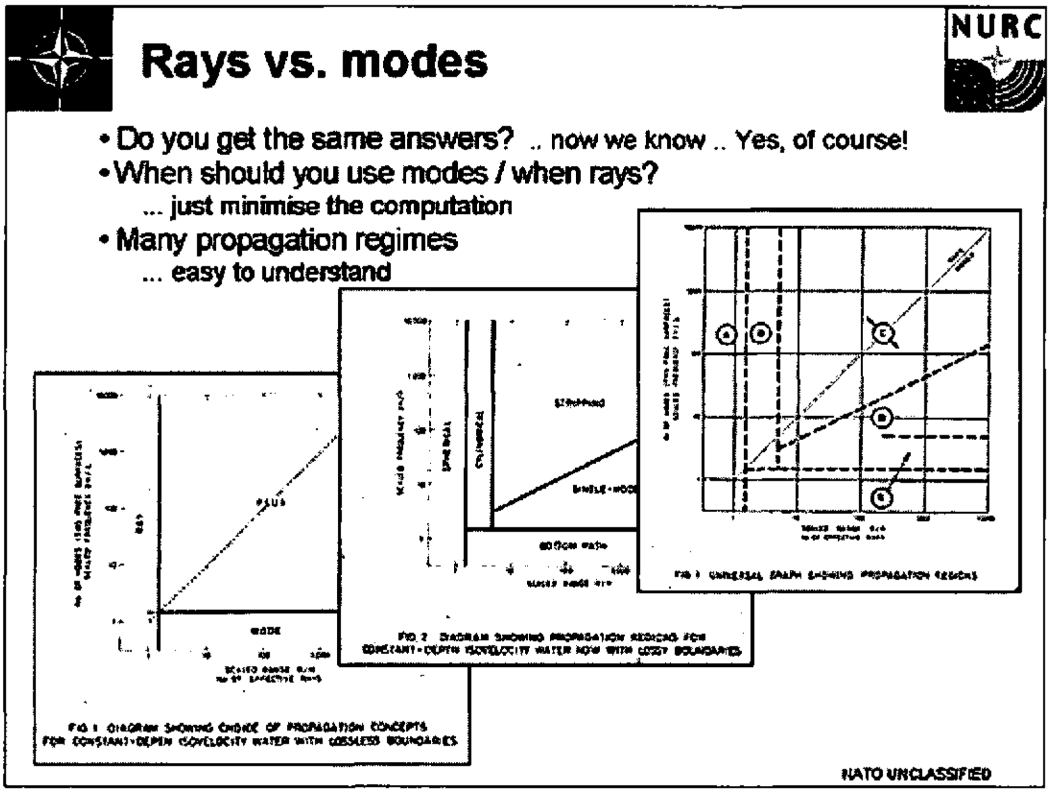


7 So I'd like to start by just going through some of these ideas that Weston originated – his legacy. Mike Ainslie gave me a pile of Weston's overhead projector slides that he had digitised, and I will show you a few of these as we go along.



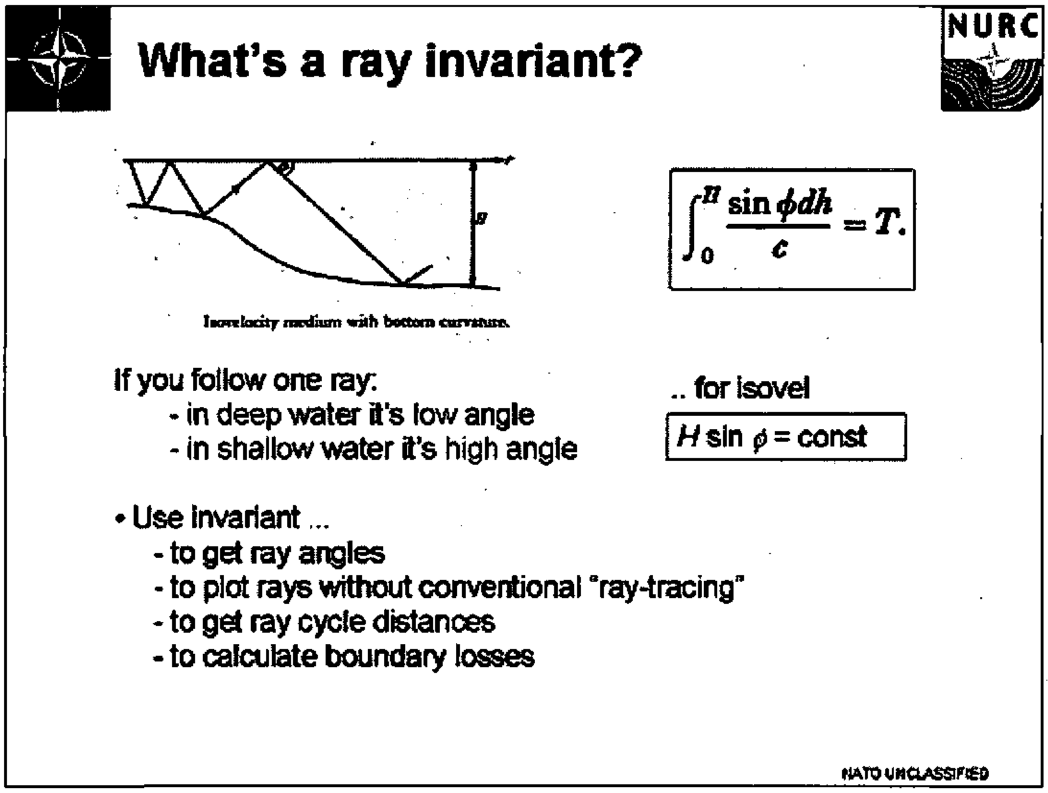
8 Weston did a lot of things but these are the ones that have most relevance to sonar performance. I'll say something about each one in a minute.

- rays vs modes
- ray invariants
- acoustic flux
- Rayleigh reflection loss
- effective depth
- optimal pulse design
- fish.... that's a joke – in the style of David Weston – Ha, ha, ha!



9 In the early days there was a lot of controversy about whether modes and rays would give you the same answer, which was the real truth, etc. Weston came up with these scheme – these are his diagrams appearing in several places. The message was "do what ever is computationally easier": if there aren't many modes, do modes; if there aren't many rays do rays.

Still, strange things happen. At long ranges rays are, in the strict mathematical sense, chaotic. But modes at the same time are not! We won't go into that, though!

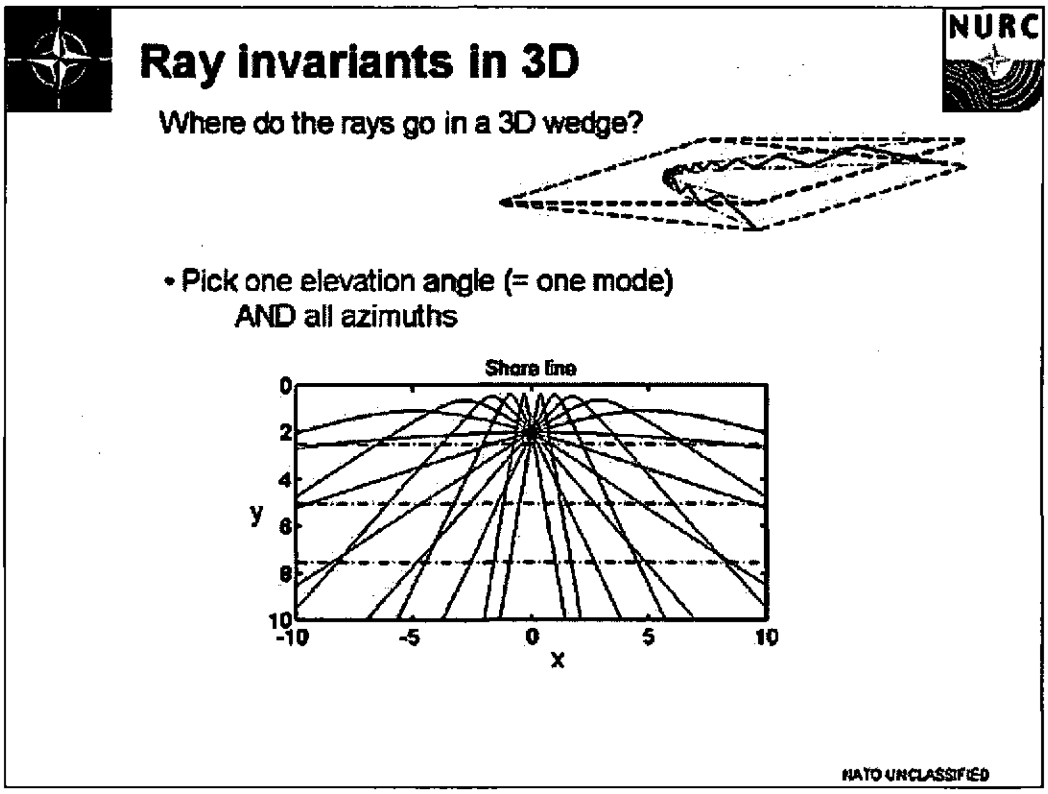


10 What's a ray invariant? Well it's that – on the right[4] It says that if you follow a ray from deep water to shallow, the ray gets steeper, but in a reversible manner. For instance, for isovelocity it would look like this[5]. It's closely related to the way a mode squeezes in between the boundaries.

This means that you can get ray angles anywhere without any ray-tracing. So you can get ray cycle distances and the boundary losses.

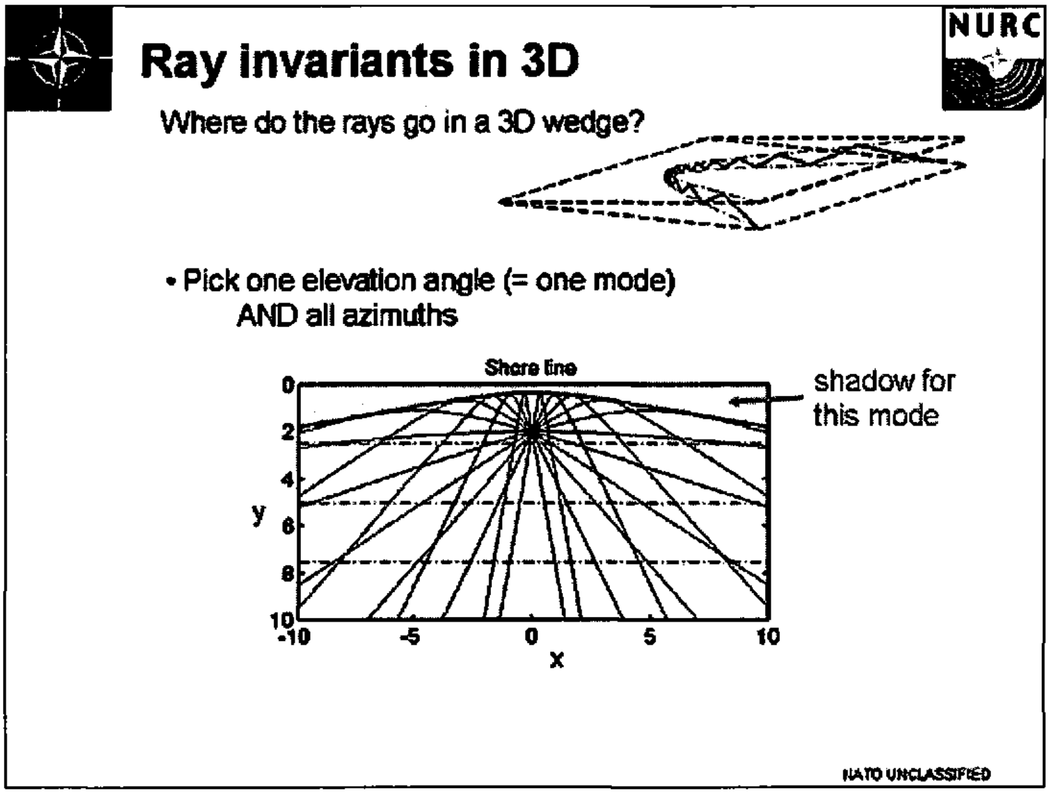
[4] Editor's note: See the equation for T (top right) and explanatory drawing (top left)

[5] Editor's note: See the equation $H \sin\phi = \text{const}$

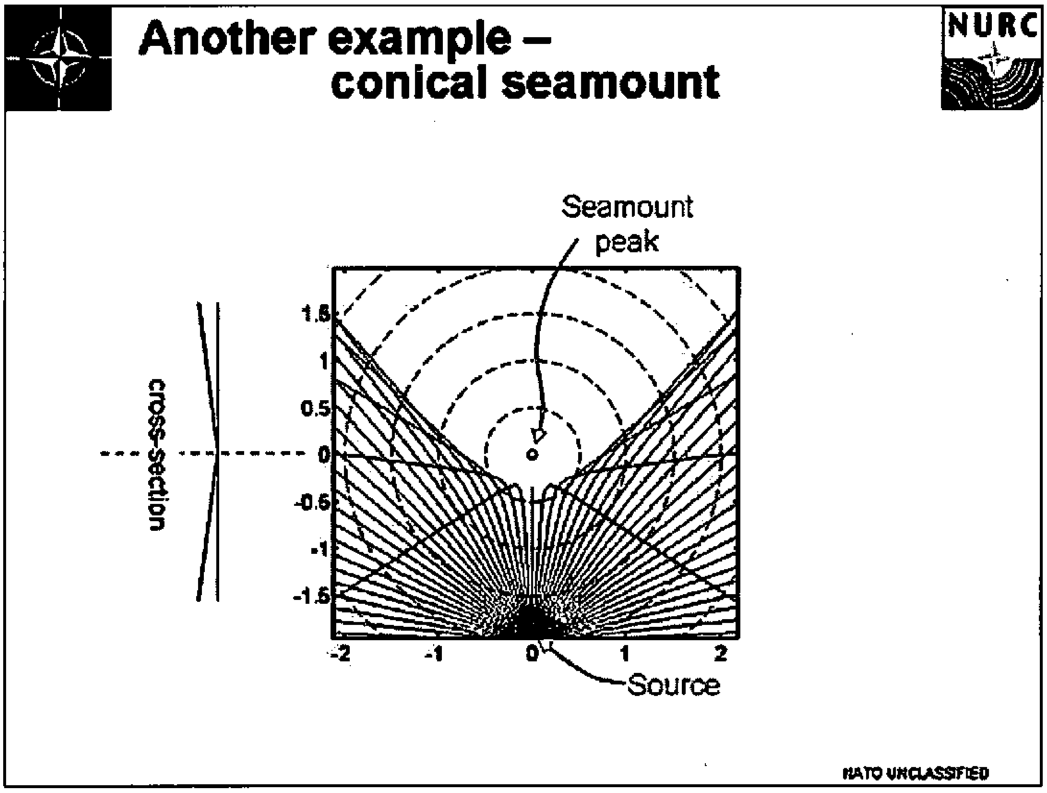


11 I started using ray invariants when I was trying to understand what rays did when they bounced around in the Norwegian Sea. Imagine a wedge shaped ocean like this[6] with rays zig-zagging round. Every time they hit the bottom they curve a bit, and it turns out that you can work out exactly where they went. You get this sort of fountain of rays in plan view – here's the shore line. So if you follow all the rays that set off at one vertical elevation angle but any old azimuth you see what a single mode does. ...

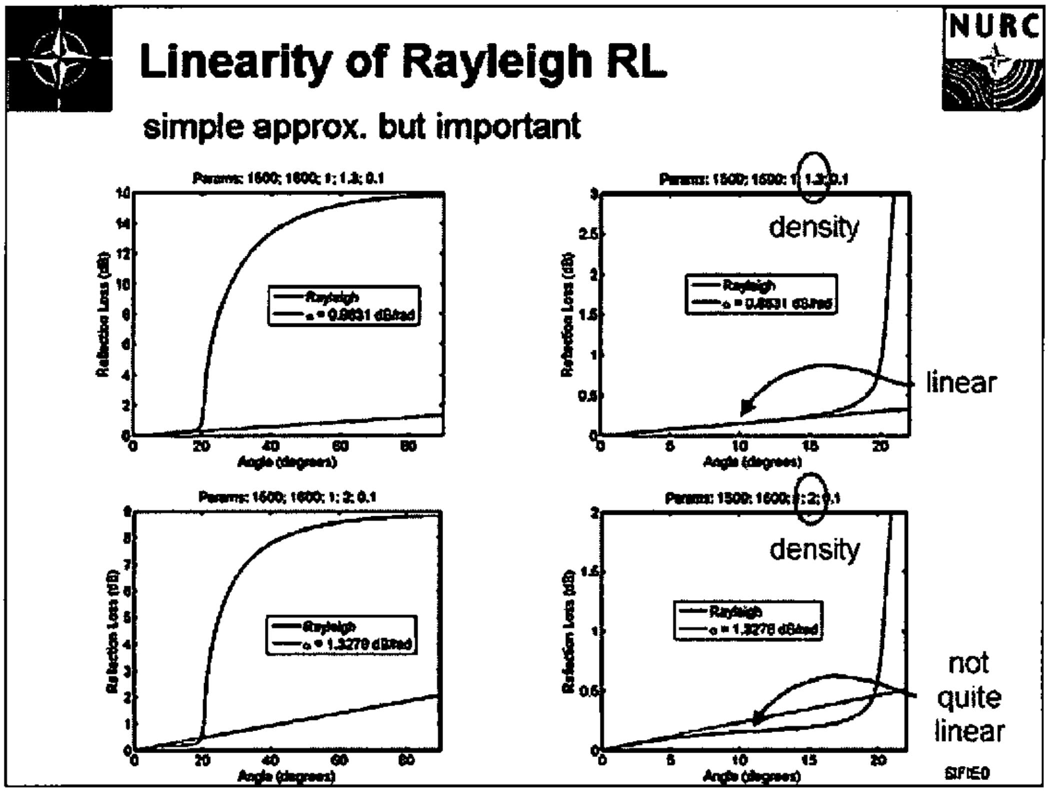
[6] Editor's note: See upper graph



12 .. and you get a shadow for that mode. In fact each mode has its own shadow.

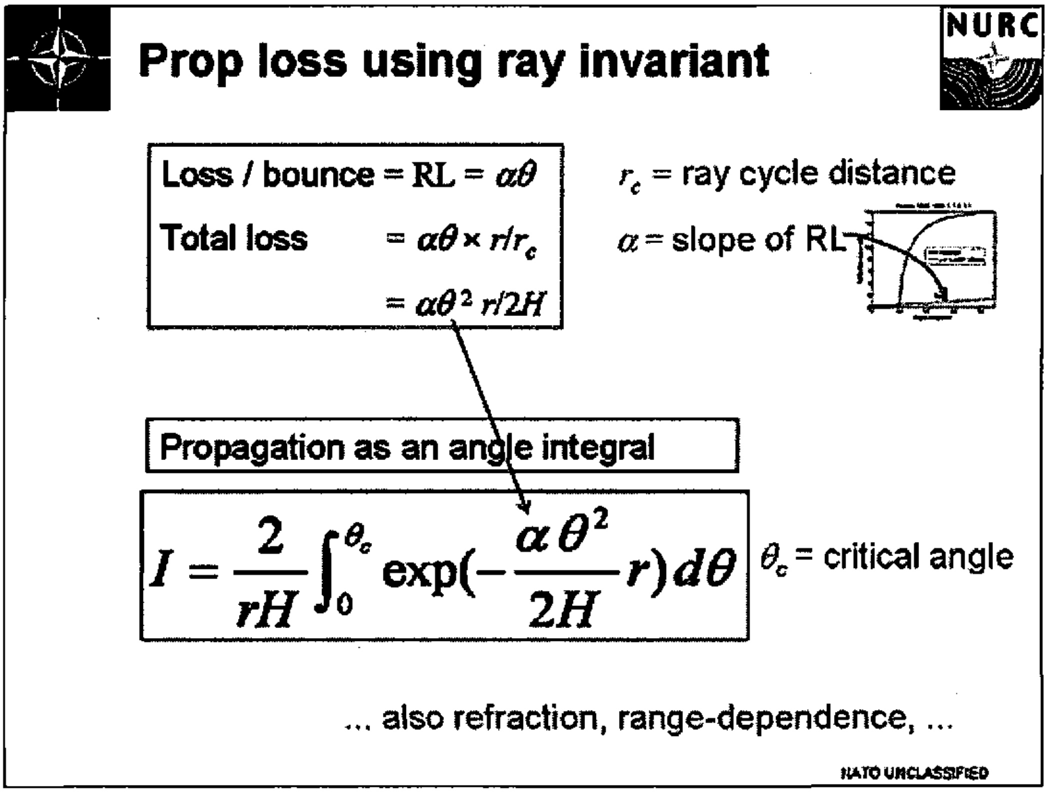


13 You can get some quite interesting things happening by pure thought. For instance here's a conical seamount with a shadow behind it. Notice that the shadow is not like a geometrical shadow – it's a lot broader.



14 Moving on a bit to reflection coefficients – well, Rayleigh invented reflection coefficients, but Weston showed that you could explain an awful lot just from the fact that the first bit here[7] is linear. Blowing this up a bit we see that sometimes it's extremely close to linear, but not always. It's possible to show that this depends 99.9% on density. In other words there's a better approximation that in the limit is linear, but the whole thing is multiplied by a factor that's a function of density only.

[7] Editor's note: See the graphs top left and (zoomed) top right



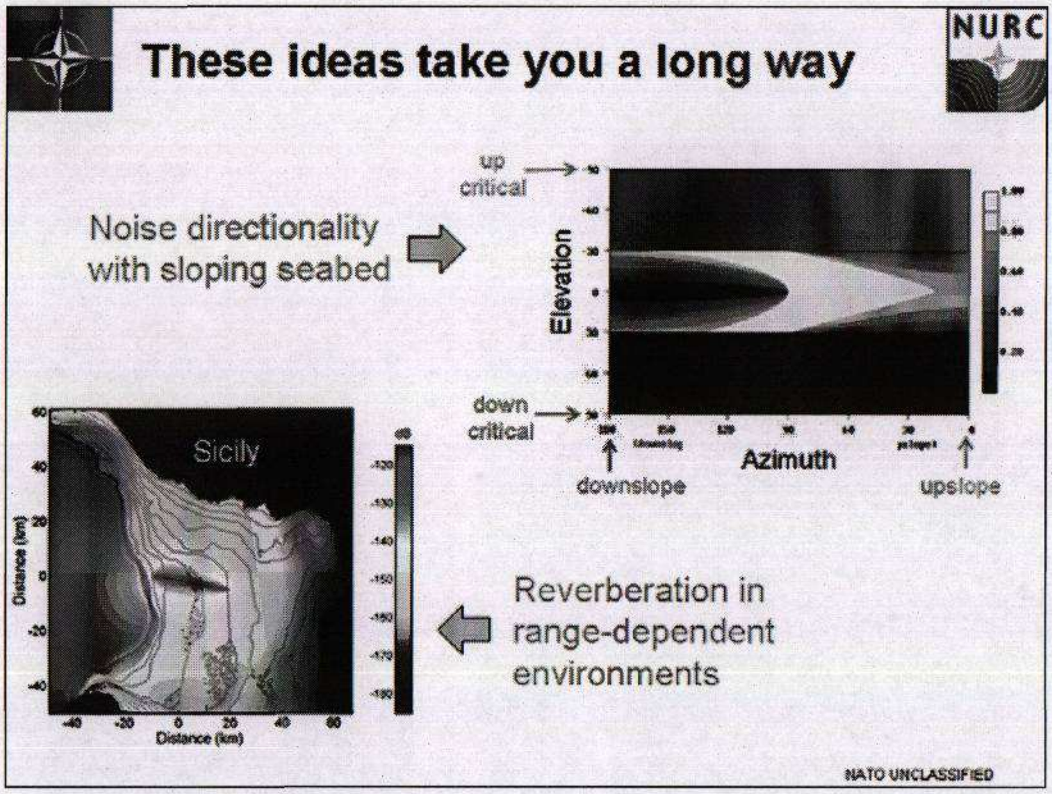
15 What can you get with this? Well you can bung it into a formula and get propagation loss, and this can be extended to range-dependent environments, refraction, and so on.

Reflection loss is related to angle like this[8]. The number of bounces is range over cycle distance. So the boundary loss goes like this[9]. Then you integrate over all angles, and you have the intensity at that range.

---

[8] Editor's note: See the equation RL = $\alpha\,\theta$

[9] Editor's note: See the equation Total loss = $\alpha\,\theta^2\, r\,/\,2\,H$



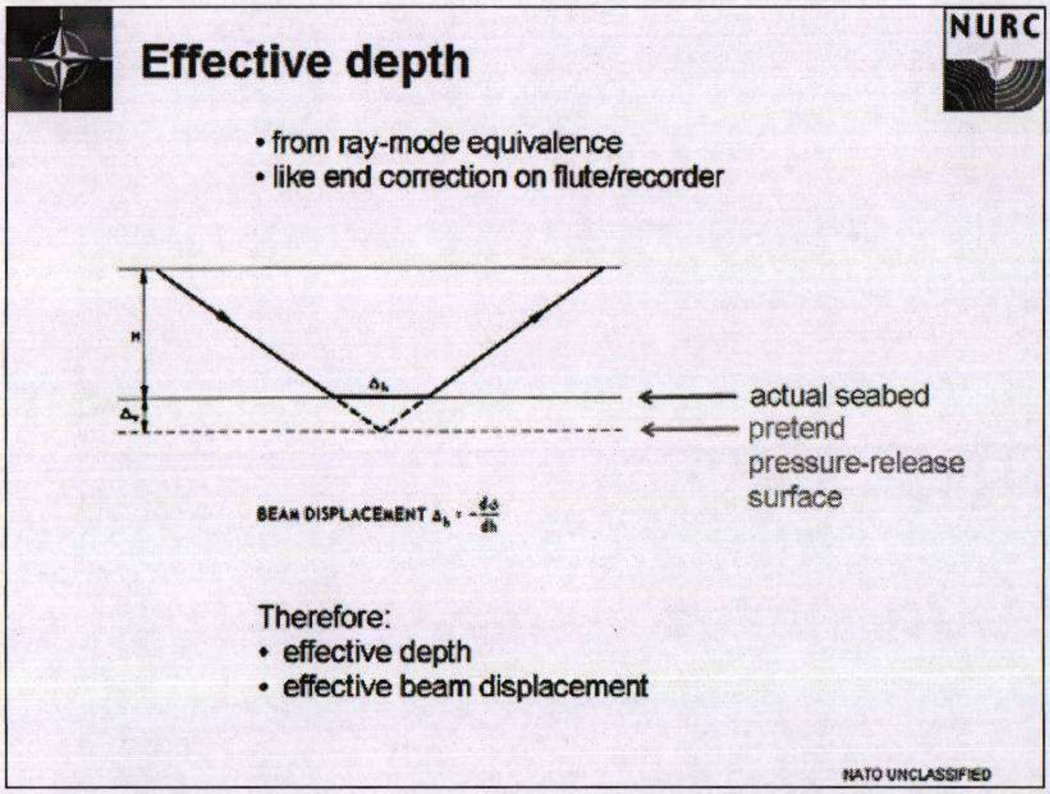
16 Using these ideas you can get a long way, not just with propagation , but with ambient noise, reverberation, and signal excess.

This[10] is noise directionality as a function of elevation angle and azimuth at a point on a slope. You get a lot coming from upslope and not a lot from downslope. And everything is inside the critical angle.

This[11] is bistatic reverberation STILL USING A FORMULA in a real bathymetry between Sicily and Malta.

---

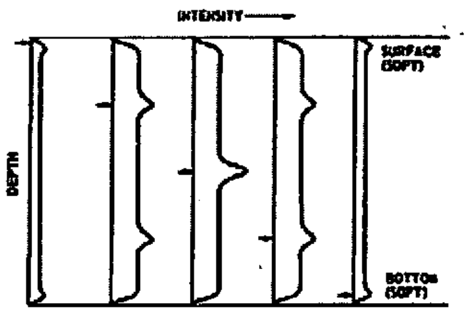
[10] Editor's note: See the graph "Noise directionality with sloping seabed"
[11] Editor's note: See the graph "Reverberation in range-dependent environments"



17 Another one of Weston's ideas that came out of reconciling ray and mode propagation was the idea of an effective depth. The reflection coefficient in the total internal reflection regime behaves like a phase change that's a function of angle. But if you invent a pressure release surface that's just a little bit further back (a fraction of a wavelength) you get very nearly the same answer for the complex amplitude. It's as if the ray crept along the boundary for a bit – a lateral shift. It's also the same as the end-effect on a flute.

Average intensity vs depth

NURC



When you add up all the modes
intensity vs depth is flat except for a dimple or two
at complementary depths of the source

NATO UNCLASSIFIED

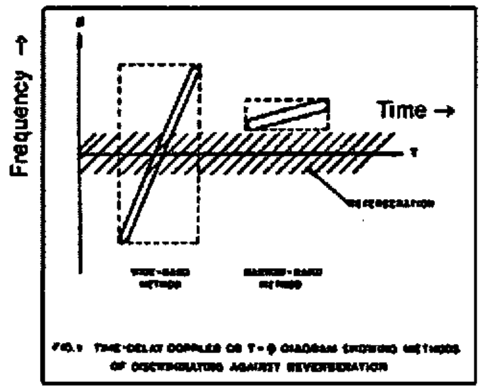
18 If you want to see wood for trees, averaging somehow is a good idea. One of the things Weston investigated is what you get when you add up the squares of all the modes. Most of the time they average out to the same number, but when you look at the depth of the source (where the arrow is) or its complementary depth you get a little dimple. This is because you're taking the average of sine to the fourth rather than the square of the average of sine squared.

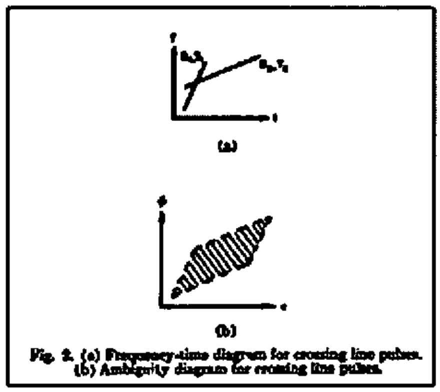
Nowadays it's the sort of thing that you can demonstrate very easily in Matlab without using your brains at all!

NURC

Tx Pulse Design

Frequency – time / "Ambiguity" diagrams
- Design FM sweeps to:
  - optimise target Doppler
  - minimise range error
  - reject reverb

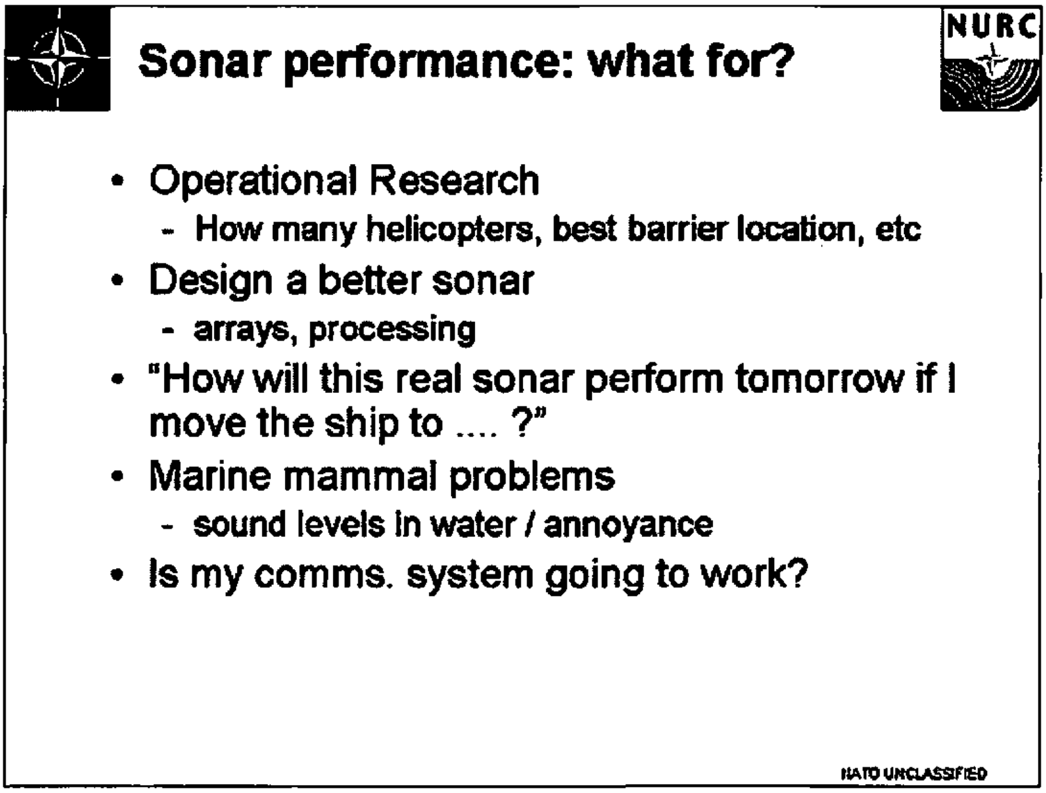




NATO UNCLASSIFIED

19

Finally he did a lot of thinking about transmit pulse design and ambiguity diagrams. The ambiguity being that with an FM sweep you can still get a good correlation match with a Doppler shifted target, but its range will appear to have shifted. There's a whole load of trade-offs with the target alone but also when you consider reverberation.

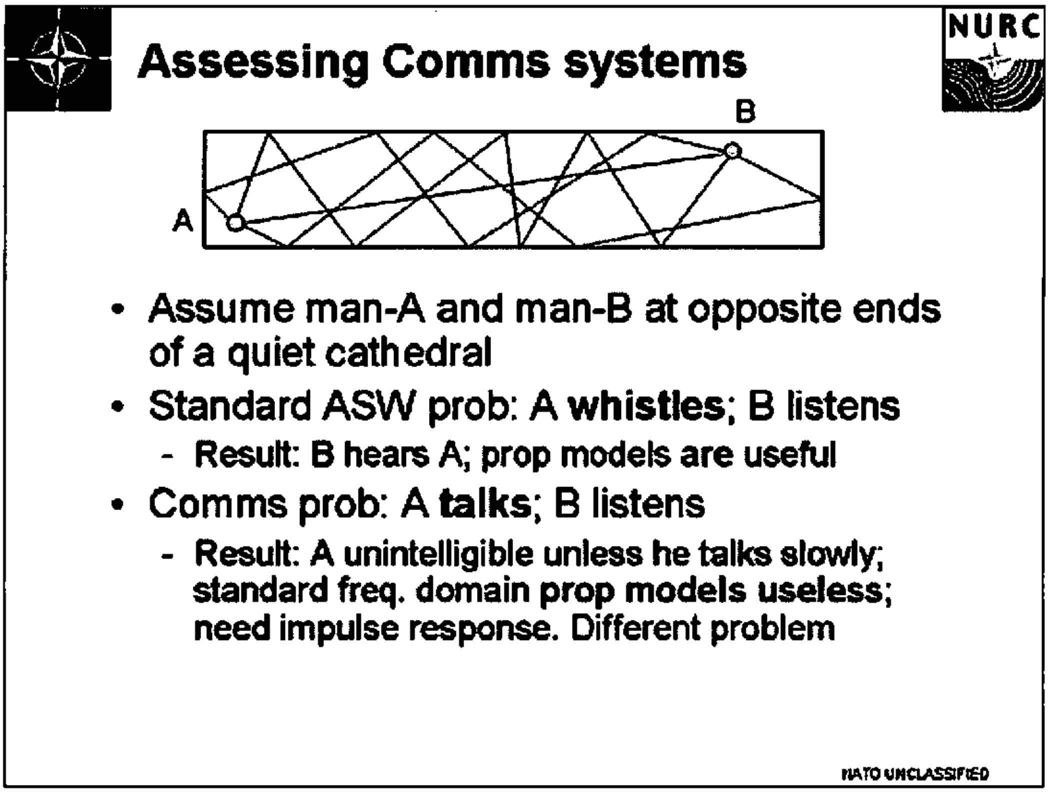


20 Now I want to move on to sonar performance itself. There's a number of reasons why you might want to assess a sonar's performance.

- Op Res: You might be tackling a higher level problem such as how many helicopters does our force need, ... where should I put barriers, etc
- You might be thinking of the whole sonar, but from a sonar design point of view. What processing? How big should the arrays be?
- Naval operations: what happens if we move this ship to there tomorrow.
- Marine mammals: We get used to the idea of the processing reducing the noise, and we think of correlation peaks that are much spikier than the actual pulse sent out. So there's another issue of what does the sonar sound like to a live ear in the water, regardless of the fancy processing that happens in the sonar receiver?
- Another question is is my comms system going to work, and this is quite different from the traditional type of assessment problem

21 So I want to illustrate this with some project experiences I had when I was at BAe[12], often with David Weston and sometimes with Mike Ainslie.

[12] Editor's note: British Aerospace, now BAE SYSTEMS



22 Assessing comms is one of my favourites. To see why it's different imagine two blokes at opposite ends of a very quiet cathedral.

- In the standard ASW problem man-A whistles and B listens. Result: prop models are OK
- In comms: man-A talks and man-B hears "der-der—der---daw. ... der-der—derdaw. ... ". He can hear things but calculating levels is useless. You need the impulse response, and you just have to talk very slowly.

It's a different problem.

UK Sonar Modelling Handbook

M Ainslie, H Ashworth, D Weston

- A guide for non-specialist calculations:
  - Detect, classify, localise, range ... performance
- Active Sonar Eq / Passive Sonar Eq
- Define all the terms for all eventualities –
- There may be horrible compromises BUT
- Otherwise the non-specialist has to make impossible decisions – and may get crazy answers!

NATO UNCLASSIFIED

23 This project is very relevant to this symposium, and I think it's where Mike first got "hooked" on this kind of problem. David Weston was being an expert consultant helping us disentangle the Sonar Equation and try and write down what non-specialists should do in this UK document called the S.M.H.[13] Basically it's trying to cover all eventualities, and that's difficult to do. There were some horrible compromises, and David kept saying, "well, it all depends", to which I answered "yes but YOU CAN'T EXPECT the non-specialist to make the compromises – WE have to make the decisions!"

[13] Editor's note: Sonar Modelling Handbook

UK "realistic" Propagation Loss benchmarks

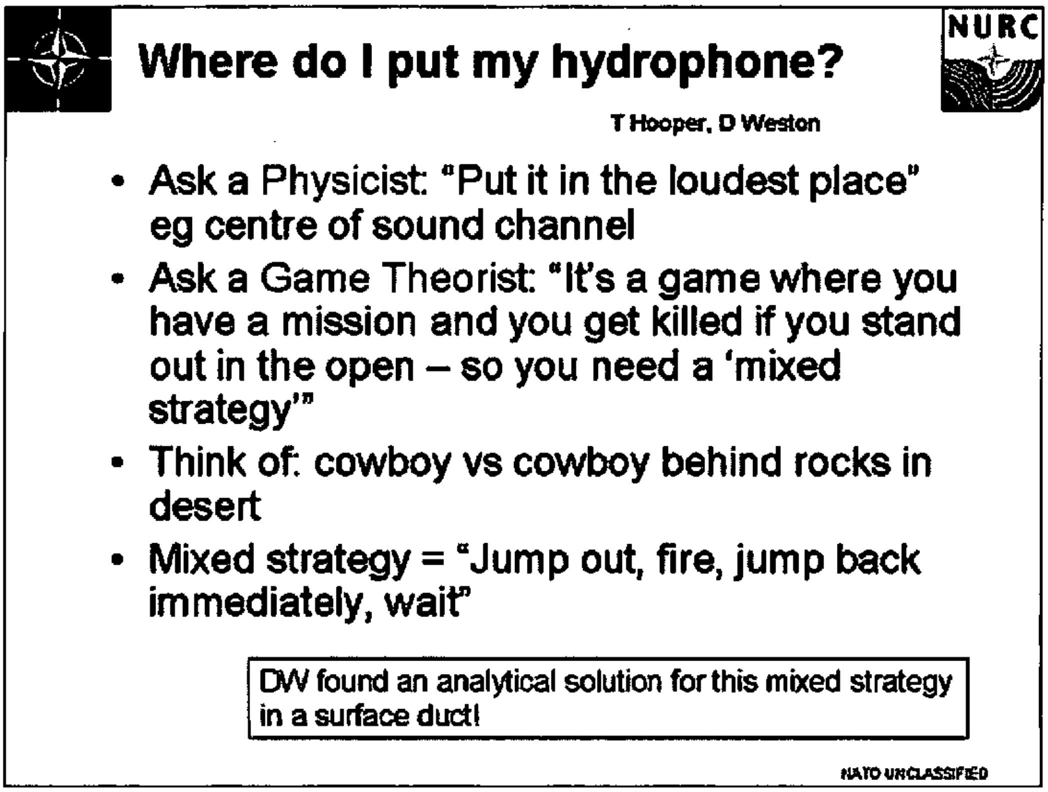
M Ainslie, R Levers, G Kirby, D Weston

- Needed some way of averaging TL(*r*)
  - eg "thick pencil through the wiggles"
- Thought of variable width smoothing (since fluctuations tend to be more rapid at short range)
- stumbled on the point that:

> a running range average of TL(*r*)
> (window width ∝ range; $w_r = a \times r$)
> is (more or less) equivalent to
> a frequency average of TL(*r*)
> (band $w_b = a \times f$)

NATO UNCLASSIFIED

24 Another project we worked on, but with Weston on the other side, was an attempt to set up some Propagation Benchmarks in Realistic Environments. The point was that you ran sophisticated models but you needed to know if they were right somehow. We needed to extract the essence by doing some sort of average. Because the fluctuations usually tend to be more rapid at short range a variable range sliding window seemed like a good idea. So that's what we did. Subsequently we discovered that a running range average (where the window width is proportional to the range) is more or less equivalent to a frequency average over a related bandwidth. So that was quite a useful result.



25 What DEPTH do I put my hydrophones? Now this was a revelation for me! If someone asks a physicist where's the best place to put the hydrophones or sources or submarines he says, put it in the loudest place. BUT if you ask a game theorist he will say, now look, this is a GAME where you have a mission and you get killed if you stand out in the open! What you need is a mixed strategy. For propagation you just need a table of what you get with all combinations of depths. A "mixed strategy" is what cowboys do in films when shooting each other. They spend 90% of their time behind a rock and 10% in the open trying to shoot.

Incidentally Weston found an analytical solution to the mixed strategy in a surface duct!

"Costing out" surveillance systems

J Foxwell, S Coad, D Weston

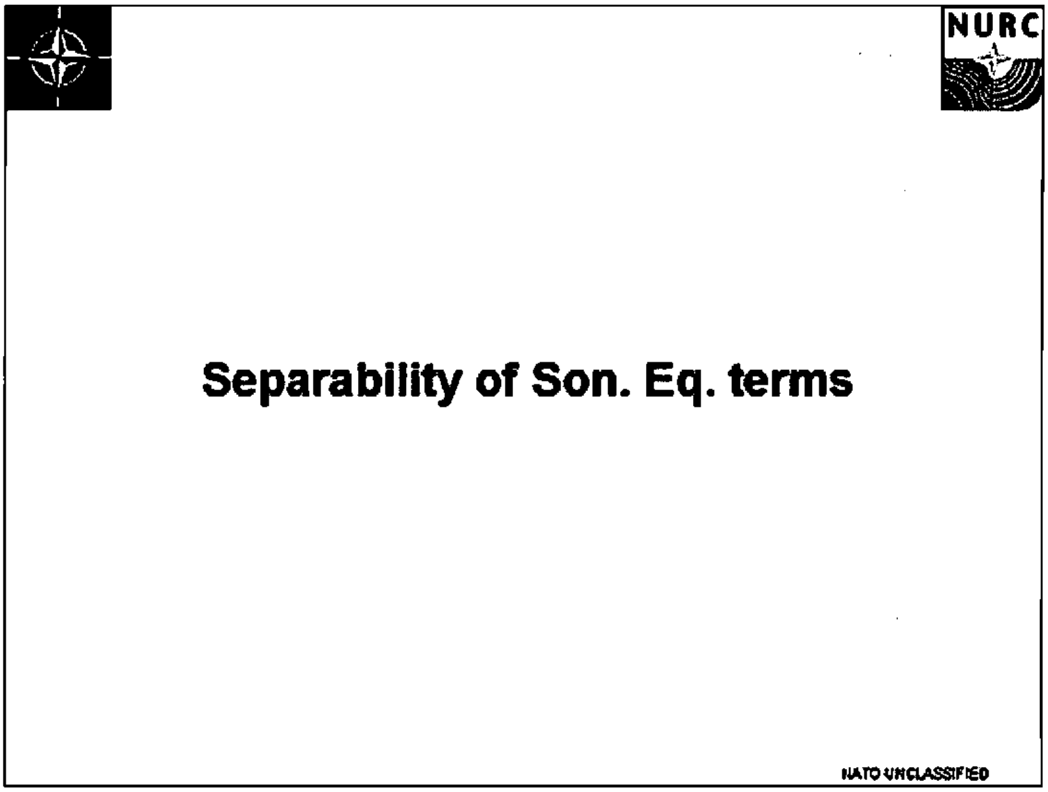
- Novel passive surveillance for UK NW Approaches (100km diamond shape)
- Hypothesize: massive arrays, distributed sensors, cabling, shore stations, ...
- Calculate propagation / estimate noise
- Get array gain etc
- Estimate area coverage through Sonar Eq.
- eg assume sph. spread. $\rightarrow$ area $\propto$ 1/noise
  BUT cost $\propto$ area $\therefore$ cost $\propto$ 1/noise

$\therefore$ 10dB increase in noise makes FACTOR of 10 increase in price!!

NATO UNCLASSIFIED 26

Costing out options is another classic application of assessment. One of the first jobs I had was to try and think of a good way of doing passive surveillance somewhere off Scotland. Again Weston was on the client side. You think of an array system or a very long line with millions of hydrophones. Given some targets, some propagation, some ambient noise, you calculate the detection ranges and see how many bits and pieces you need – therefore you get a price. What could be easier?!

The trouble is that changing the noise level by 10 dBs translates into a 10dB change in the price! Don't you mean 10% increase in price? NO. A factor of 10 increase in the price. It's a dodgy game, this!



27 Now I want to come back to another annoying thing for sonar assessors. Are the Sonar Equation terms really separable?

Interdependence TL, NL, RL

Noise / propagation:

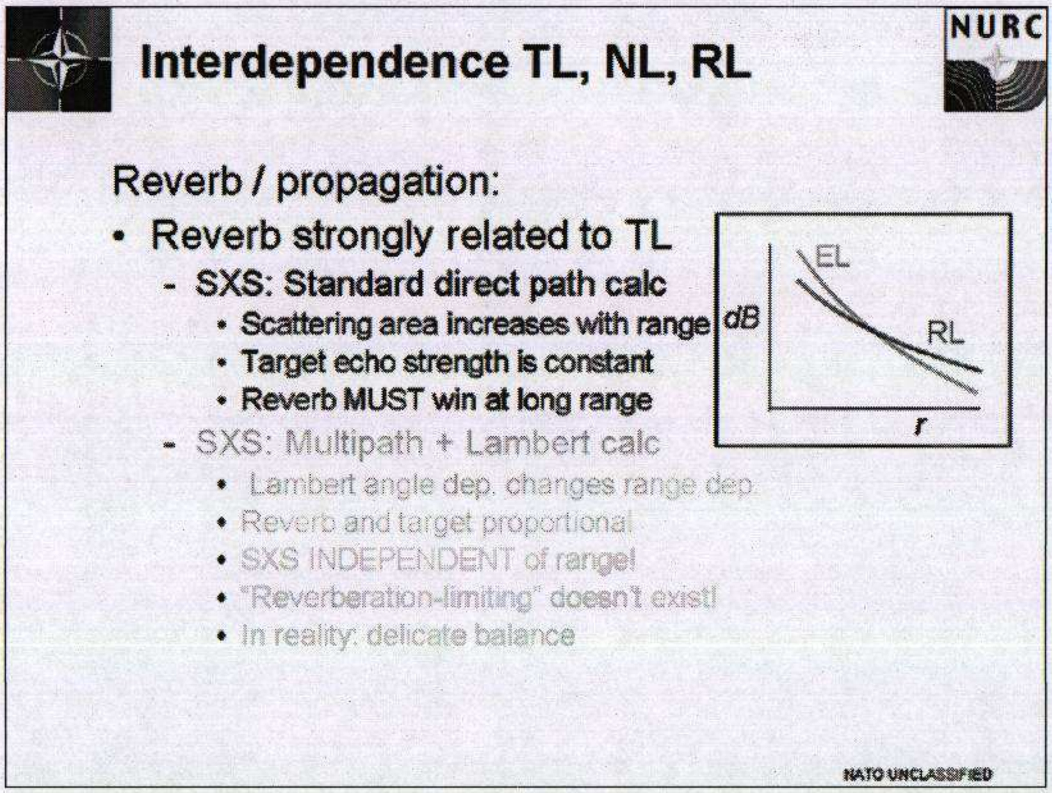
- Where can you "hear best"? Bathroom / living room?
  - Bathroom: Good propag.; Loud noise
  - Living room: Poor propag.; Weak noise
  - So ... ? Where ... ?
- Need self-consistent terms
  - Don't model TL then measure NL
  - Don't model TL then get NL out of a book!
  - Model TL and NL together → SXS

NATO UNCLASSIFIED 28

To illustrate this you could ask the question, where can you hear best in a house – the bathroom or the living room. I'm talking about an English house with carpets, curtains, etc! In the bathroom there's GOOD propagation but LOUD noise/reverberation. In the living room there's poor propagation but WEAK noise. So which one wins?

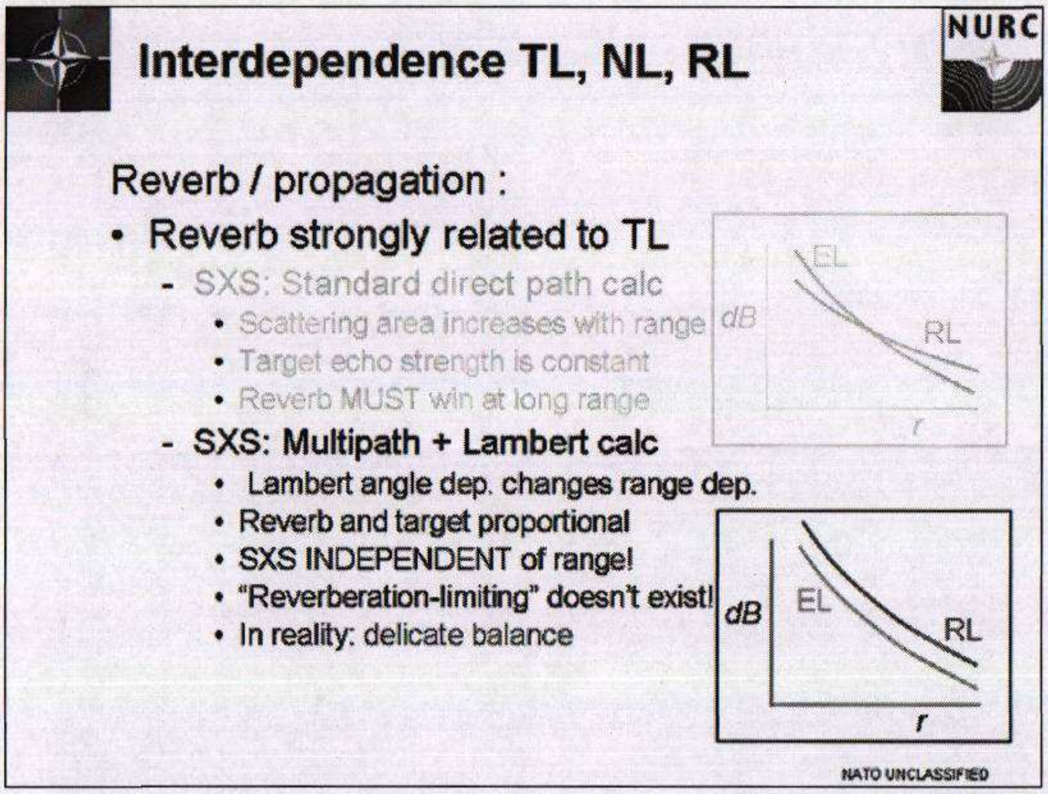
You need to be very careful and make sure that you have self consistent terms and models.

Don't model TL then measure NL. Don't model TL then get NL out of a book!



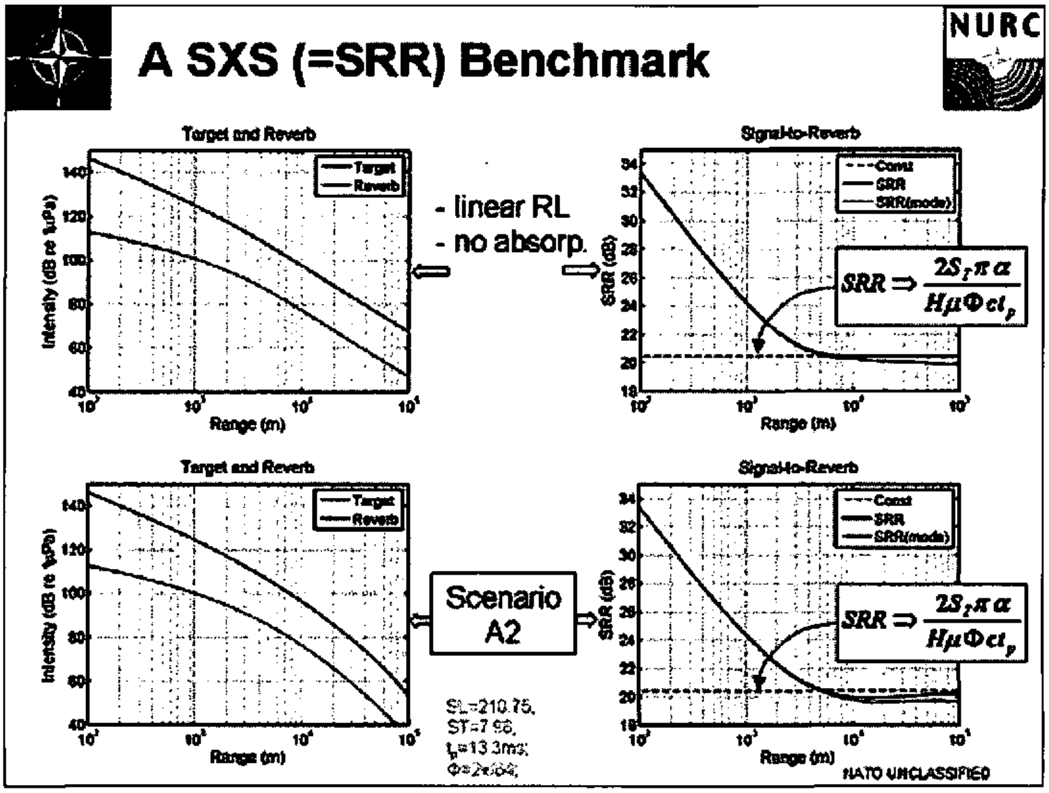
29 It's obvious that reverberation is strongly related to the propagation. But usually you might expect reverberation always to wipe out the target at long range. They both suffer some propagation loss, but the target echo strength is constant while the scattering area gets linearly bigger as range increases. So you get reverberation limiting at this[14] intersection. ....

[14] Editor's note: Intersection between curves labelled "EL" and "RL"



30 ... but if you take account of the way the scattering law depends on angle – for instance Lambert's law – you find that the increase in area is exactly compensated by this and the reverberation and target echo decay in parallel. So reverberation limiting doesn't exist. Instead you have noise limiting.

A corollary is that you can see as far as you like by increasing the source level. I suspect that this an "empirically known fact" and this is part of the reasoning behind current loud sonars and problems with marine mammals.



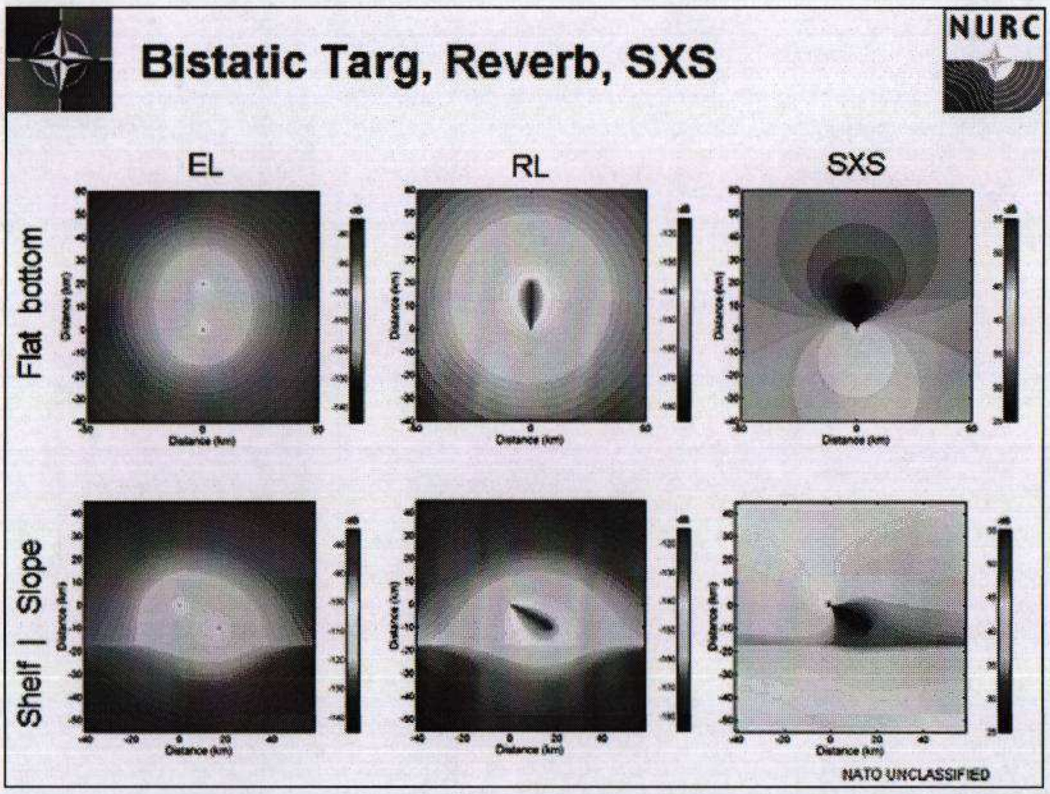
31 To make this a bit more quantitative and pertinent to this workshop's Test Cases I can put this all into an analytical model.

At the top on the left is target echo and reverb, and on the right is the signal to reverberation ratio. You see that it goes flat beyond a certain range. The value of this "plateau" is just a number – the (linear) target strength × reflection loss slope (alpha), divided by water depth, Lambert's mu, horizontal beam width and spatial pulse length.

NOTE that if you make the bottom MORE lossy you get HIGHER SRR[15], not lower!!

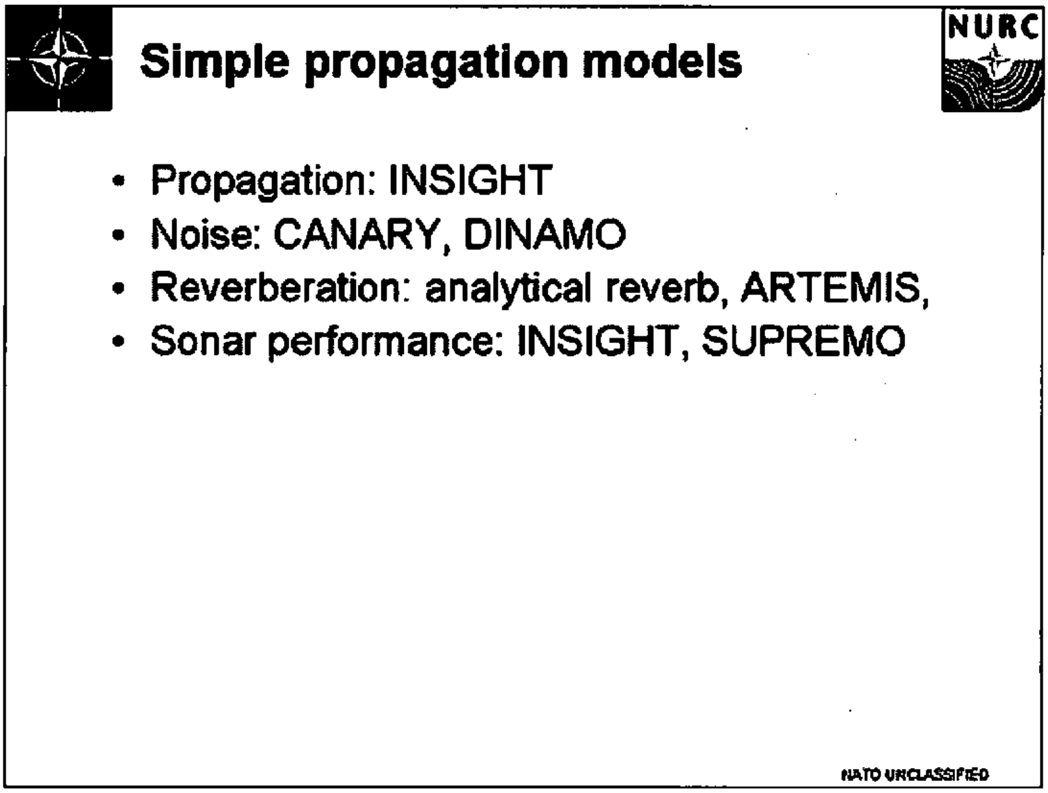
The pictures at the bottom are for the Test CaseA2.I[16] now including the non-linearity of the reflection loss and absorption at 1kHz. The result is almost the same.

[15] Editor's note: Signal to reverberation ratio
[16] Editor's note: See the paper by Zampolli et al in these proceedings describing test scenario A2.I

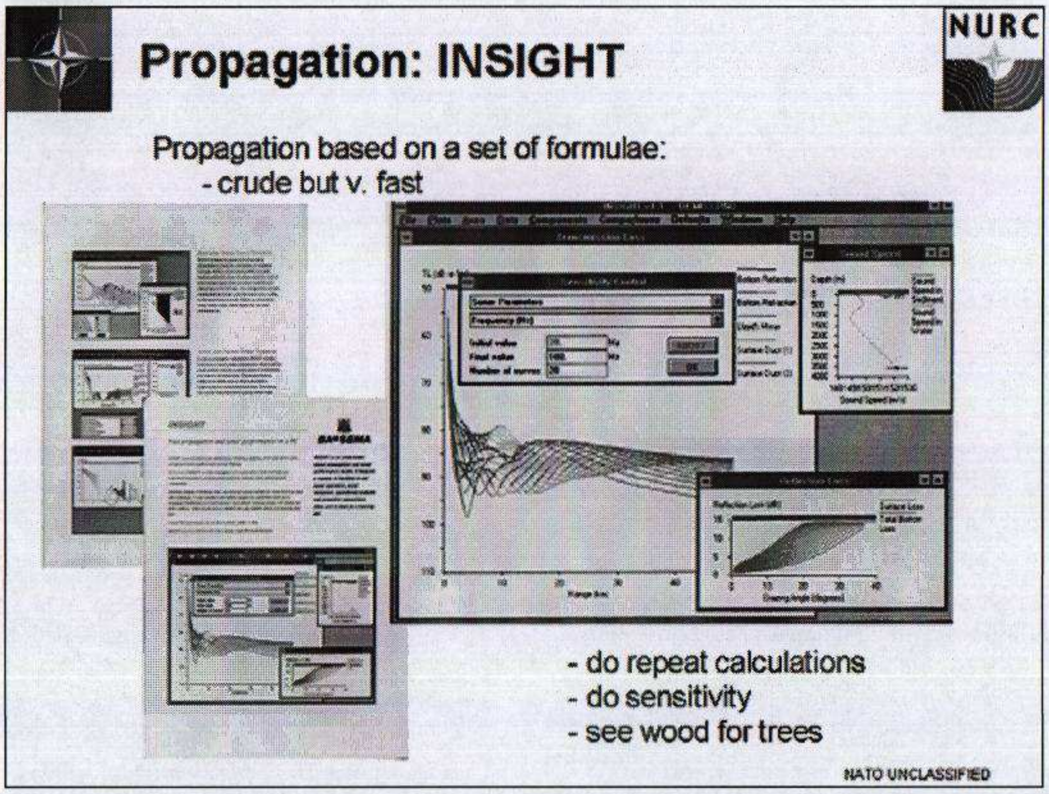


32 This is what happens with the same formula for bistatic sonar. In the top line the bottom's flat. In the bottom line there's a shelf at the bottom of the picture and a slope going deeper towards the top. On the left is the familiar "ovals of Cassini" for the target echo. The reverberation always has this kind of cigar shape. The signal excess is more or less flat except for the area of poor SXS[17] in between source and receiver and the small area of good SXS just behind the receiver. You still get similar behaviour when the bottom isn't flat (bottom right).

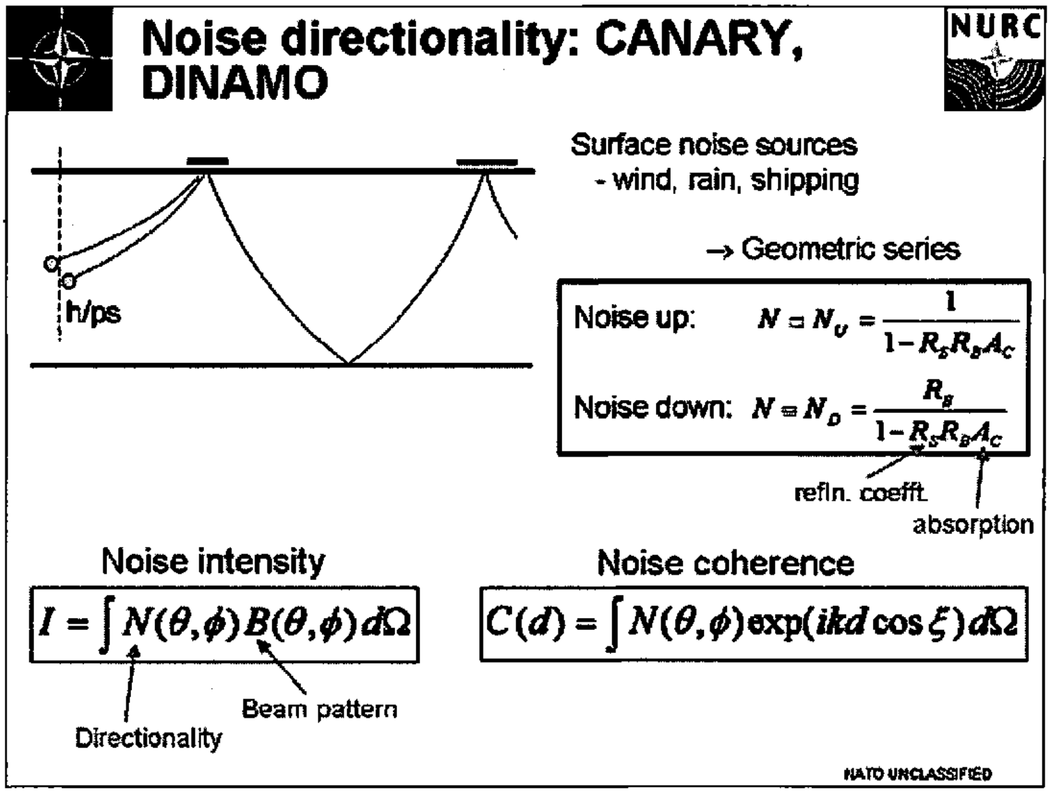
[17] Editor's note: Signal excess



33 Now, I've talked about some formulae but there are a lot of things you can do in between formulae and parabolic equation or adding up modes. These are some of the variants I've been involved with, and I'll briefly say something about each one.



34 INSIGHT started off as a propagation model and ended up as a sonar performance model. Mike and I spent years fooling around with it. What happened was that we wanted to check whether the wiggly lines we get from other models, such as the parabolic equation made sense or not. To do this we made overlays with a set of simple formulae that all had their separate regimes of validity. Then we realised that if stuck these formulae together that made a model in its own right – INSIGHT. Because it was constructed from formulae it was potentially infinitely fast.

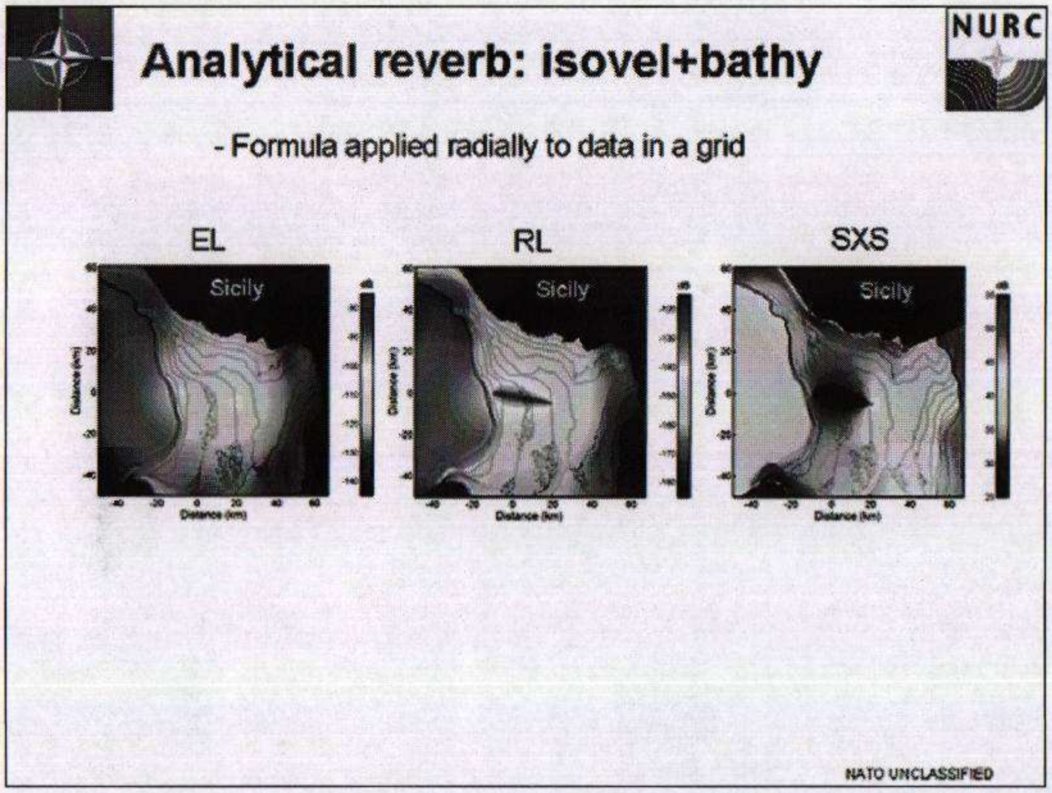


35 CANARY and DINAMO are noise models. CANARY was a research model that calculated noise directionality and noise coherence for all sorts of arrays, including conformal ones. DINAMO calculated noise levels as a function of locality. I think it got used on UK submarines.

If you think about noise emanating from all the points on the sea surface (wind, rain, etc), you find that when you integrate over the area, first it can be transformed into an integral over angle, then the contributions from all the zig-zag rays turn into a geometric series.

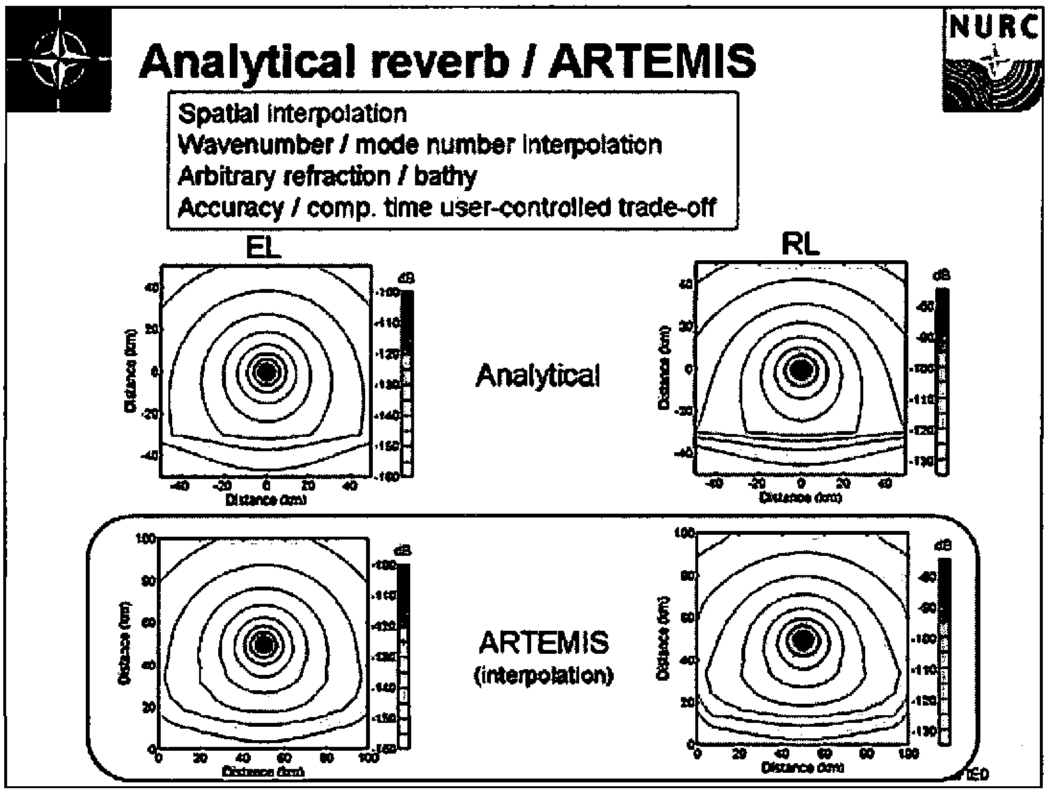
So the "up" noise looks like this[18] and the "down" noise looks like this[19]. So there's a simple formula both for the noise level and for the noise coherence.

[18] Editor's note: See equation for "Noise up"
[19] Editor's note: See equation for "Noise down"



36 I've already mentioned some analytical formulae for reverberation. Those were for parametrised environments, ie shelf depth, bottom slope, etc. It's also possible to operate these formulae for bistatic sonar along radials from the source and receiver, but you insert effective depths calculated from a grid. This is target echo, reverberation, and signal-to-reverb-ratio between Sicily and Malta. The whole lot takes a couple of seconds on a PC.

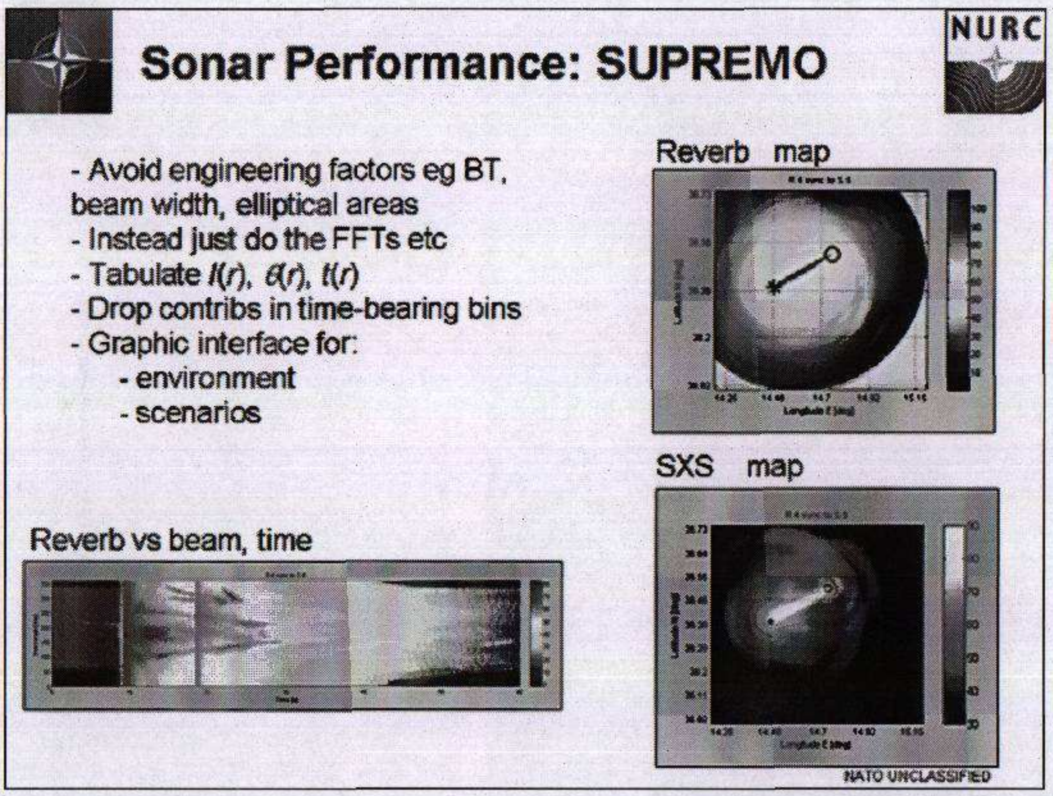
In principle any of the parameters in the formula can be gridded without slowing anything down, eg reflection loss (slope or critical angle), Lambert constant, ...



37 ARTEMIS is a numerical version of this reverberation formula that works in a general environment. It's general in the same sense that the adiabatic mode sum is general. It treats the mode sum as a continuum (It's possible to show that a continuum of modes is the same thing as a continuum of eigenrays which is the same thing as Weston's flux.)

So it does spatial interpolation and wavenumber interpolation. The user can control the trade-off between accuracy and speed.

This is a monostatic case. At the top is the formula I've been talking about already. At the bottom is ARTEMIS.



38 This is another , different step in the direction of numerical modelling. SUPREMO is a shell that allows the user to insert his favourite propagation model as long as it calculates intensity as a function of vertical angle and travel time. It then tabulates what you're going to need and puts the contributions in the correct time bins.

One feature is that instead of putting factors like BT into the sonar equation it lets you set up a genuine FM pulse (using its graphic interface) and works out what the correlation gain is by actually doing FFTs and a cross-correlation. It does some similar "tricky" things in getting from the "dots-in-bins" to a picture like this of reverberation vs two-way travel time and bearing.

39 Finally a word about the future. I don't know anything about the future, but there seem to be a few types of thing that need to be assessed, eg

harbour protection, divers, AUV[20] systems, gliders. In a way there just the old sonars; in another way there may be lots of them and so the problems change.

There are other areas that aren't really assessment areas yet, but they easily could be: striations, statistics. ... and how do you assess a trainer / stimulator? What happens if some operation relies on geoacoustic inversion for its bottom reflection. What do you do then?

[20] Autonomous underwater vehicle

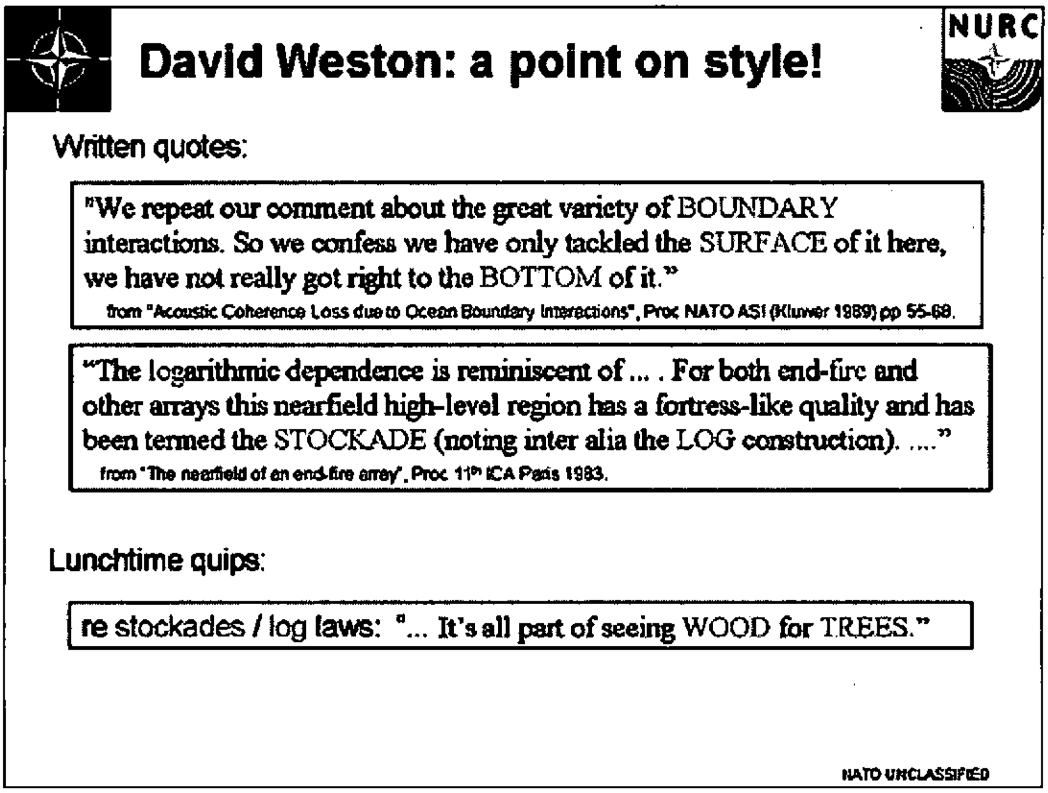
Conclusions

- Weston's legacy (for Sonar Performance alone)
  - flux, ray inv, reflection loss, ducts, Tx pulse design
- Sonar Perform. Assessment – many aspects
  - standard / comms / game theory / costing
- Separability of Son.Eq. terms
  - They're not really separable
  - Need self-consistent models
- Simple Models
  - Get the mechanisms right
  - Don't get caught up in the details
  - Need many reruns: Speed up maths / computation

NATO UNCLASSIFIED

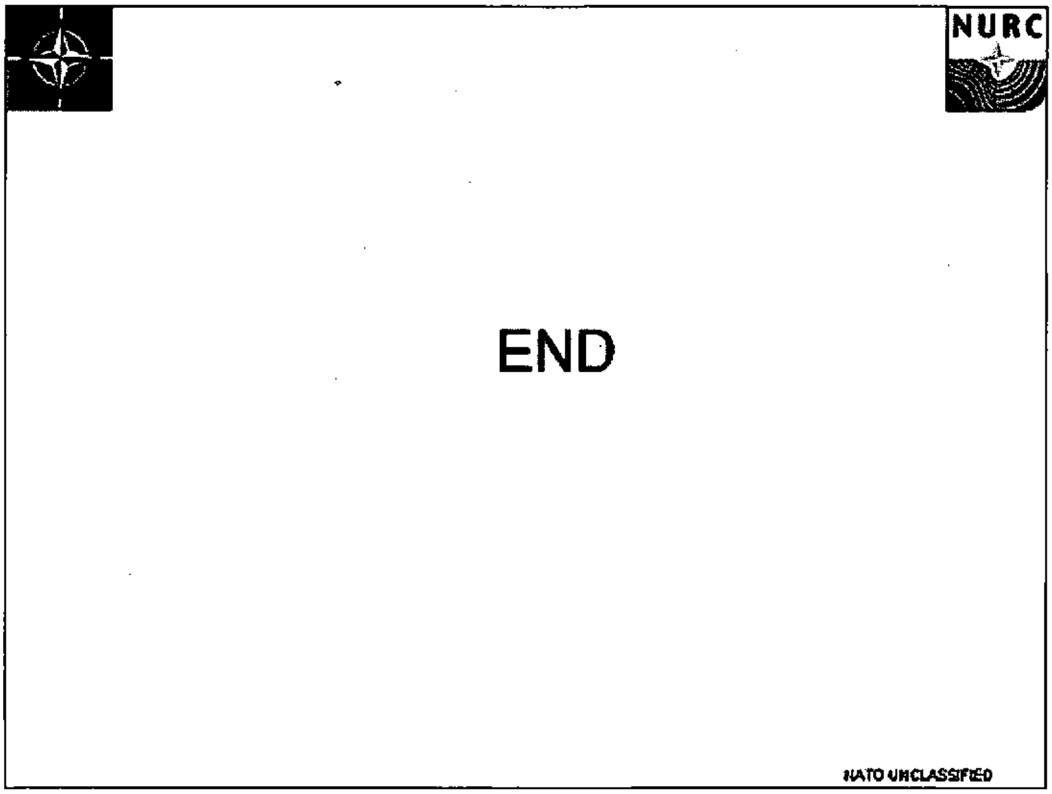
40 So, I've talked about Weston's legacy (actually only part of it), the many aspects of Sonar Performance Assessment, Separability of the Sonar Equation terms, and Simple models.

In assessment I think it's more important than anywhere else to get the sonar mechanisms right and don't get caught up in the details.



41 Finally I couldn't resist putting in some of the Weston corny jokes! He'd never get away with it these days.


Just one other thing
NURC
Don't forget the fish!
- DW
NATO UNCLASSIFIED


NURC
END
NATO UNCLASSIFIED