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Science, Technical Innovation and Applications in Bioacoustics: Summary of a Workshop

Editor: John G Rees

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BRITISH GEOLOGICAL SURVEY

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Science, Technical Innovation and Applications in Bioacoustics:

Summary of a Workshop

Allen R., Anderson T., Atlas L., Clark C., DeVaud F., Doust, P., Fay J., Geen, M., Gunn D., Hastings M., Haun J., Hayward G., Jackson P., Kennedy R.,Kirsteins I., Langhorne N., Linnett L., McDicken N., Moore P., Rees J.G., Rothe M., Simmons J., Simmons R., Waters D., Zimmer W., and Zorikov T.

Editor: John G Rees

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Keyworth, Nottingham NG12 5GG

Tel: 0115-936 3100 Fax: 0115-936 3200
e-mail: sales@bgs.ac.uk
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Tel: 020-7938 9056/57

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

Tel: 01392-445271 Fax: 01392-445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS

Tel: 028-9066 6595 Fax: 028-9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

Tel: 01491-838800 Fax: 01491-692345

Parent Body

Natural Environment Research Council

Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

Tel: 01793-411500 Fax: 01793-411501

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Foreword

In 2003 the UK Research Councils offered funding (£20m) to promote ‘exciting’ and ‘innovative’ research to underpin the technological requirements of the different Research Councils. By definition, the call requested a syndicated approach by academic organizations, with the overriding requirement to support several of the Research Councils and not be specific to one particular council, as is normally the case for such funding.

Appreciating the recent advances in innovative research on signal processing based upon bioacoustics, such as that being undertaken by Dr Laurie Linnett and his team at Fortkey Ltd, it was proposed that a syndicate should be set up to submit a proposal. The resulting bid entitled *“Towards an Acoustic Spectrometer”* was based upon recent developments in chirp technology which had wide ranging application; including medical diagnosis, deep seismics and geological interpretation, acoustic characterization of materials, military requirements including mine detection and identification, and telecommunications. Under the management of John Rees, it was put-together by most of the UK contributors to this report, with Dr Nick Langhorne of the Office of Naval Research Global (ONRG) acting as an external facilitator. The bid submitted in 2003 was not successful. However, it received strong support from the adjudicators, with their recommendation that it should be resubmitted for the next round of funding in 2004.

Taking advantage of this opportunity, it was decided to critically review the submission and to do this it was agreed that the ideas contained should be exposed to international experts and benefit from their critique. As part of this process, Nick Langhorne collaborated with Bob Kennedy, (European Research Office (ERO), US Army Engineer Research & Development Center (ERDC), leading to the latter setting up a workshop in conjunction with John Rees and Laurie Linnett. Funding support for the Workshop was provided by the ERO and ONRG.

The Science, Technical Innovation and Applications in Bioacoustics Workshop was held at the Marine Hotel, North Berwick, East Lothian, Scotland between 4-5 May 2004. (See Appendix I for a detailed agenda).

It involved a limited number of overview presentations by invited speakers and ample time for facilitated discussions. Participants (Appendix II) included academic and government representatives from across a broad range of relevant expertise and experience with a view to summarizing the state of the science and the gaps in knowledge, defining areas with potential for innovation, and developing a research agenda, shaped by anticipated applications. It focused upon three main topics:

- *The state of our understanding of the basic science of bioacoustics* – summarizing what we know, and what we don’t know, about acoustic signals produced by animals and how they acquire knowledge about their environment.
- *The conceptual basis for bioacoustics-based engineered systems* – Addressing the question of how bioacoustics signals can meet human information needs, what will be the characteristics of an engineered bioacoustics system?
- *Science and technology gaps* – Identifying research needs and priorities

This report details the key results from the workshop and provides an initial statement from delegates about each of these topics. Instead of reproducing what was said by delegates (the presentations of whom are contained in Appendix 3) the written report summarises the main findings of the meeting in a précised form. The report effectively is the joint product of all of the delegates who attended and contributed, not only with presentations and discussion at the time, but in writing subsequently.

The workshop, in some ways, may now be seen to have served its purpose as, upon re-submission in 2004 as the "*Biologically Inspired Acoustic Systems*" project the consortium dominated by UK delegates at the meeting have proved successful in obtaining £3.5 million support from Basic Technology for research into bioacoustics and acoustic technology areas incorporated in this report.

However, as has become increasingly apparent to those ready to engage in new directions of research in this area, the field is very wide, and many have already fallen in pursuit of similar goals to their own. Mapping a strategic course will not be easy. The information and feedback relating to past experiences in this report should prove to be very valuable as a starting point.

Acknowledgements

As editor of the workshop contributions, I would like to thank not only the main instigators behind the workshop, notably Bob Kennedy, Nick Langhorne, and Laurie Linnett, the chief architects, Julian Richmond (who with supreme efficiency performed most of the administrative responsibilities) and Colin Graham, but all the delegates for their efforts. It is hoped that in time we will see that what has been presented here is but the first of several products and initiatives that result from the event.

1 Introduction

**Nick Langhorne[1], Tom Anderson[2], Bob Kennedy[3], Norman McDicken[2], Rob Simmons[4], and
Dean Waters[5]**

[1]US Navy Office of Naval Research – Global
[2]Department of Medical Physics and Medical Engineering University of Edinburgh
[3]European Research Office, Engineer Research & Development Center, US Army Corps of Engineers
[4]Programme Management Office for Explosive Ordnance Disposal, US Navy
[5]Biology Department, Leeds University

In considering how to forward the application of bioacoustics across society, it is worth reminding ourselves that knowledge of bioacoustics has the potential to benefit a vast range of technologies of interest to different human requirements. In almost all applications, though the frequencies, band widths and power outputs used vary by orders of magnitude, they have commonality in terms of the underlying requirements for higher resolution, material characterization, better penetration through obstructive media, and the reduction of clutter and false contacts etc. Whilst it is impossible to give examples of applications across a range of technologies it is useful to consider the status of acoustic applications from two end-members, medical and military/ environmental, to show differences, but more importantly, to emphasize similarities in their requirements.

- Medical diagnosis, though working with ultrasonic frequencies (2-50MHz, 1540 m/s) has similarities with other lower frequency systems such as those used in radar systems and geological seismics. However, medical imaging normally has overriding requirements for safety, repeated use, and non-destructive testing. Unlike many of its counterparts, medical imaging has the advantage of the ability to move the person or object being examined to optimize the viewpoint, and the opportunity to introduce contrast agents (for example: micro-bubbles). Full use is made of narrow beams, non-linear propagation, scattering, Doppler, harmonics, coded pulse sequences and 3-D imagery. Nevertheless, many challenges and needs can be identified and it is believed that inspiration can be gained from a greater understanding of bioacoustics and novel signal processing concepts.
- The requirements of military/ environmental applied Bioacoustics are demonstrated by the interests of the US Navy and Army Corps of Engineers, both of whom deal with ‘the sharp end’ of technological development. In the case of the Navy, it has a remit to identify and transition mature technology in order to meet fleet requirements; the Corps of Engineers covers the provision of engineering and environmental services for the military, federal and civil requirements of the US nation. Both focus on the design, build and operation of water resources and the assessment of the battlefield environment. The Navy supports the underlying requirement for the use of unmanned underwater vehicles (UUVs) in their role as a force multiplier, and to reduce the need for divers to undertake the more mundane and often dangerous military operations. Acquisition strategy is based upon incremental capability development with emphasis on the rapid deployment of small multiple UUV systems. In addition, full consideration is given to user friendliness and affordability. Mission requirements include mine and other ordnance detection, identification, localization and disposal (including buried mines), and ships’ hull and pier inspections. Longer-term goals include cooperative behaviour of UUVs, which necessitates developing the technologies for through-water communications, sensors (including sensors for detecting explosive materials) and sensor data integration, and underwater navigation. In the case of the Army Corps of Engineers, major emphasis is placed upon the detection and disposal of unexploded ordnance and other hazardous waste material both on land

and in inland and coastal waters. These also lead to the reduction of site clean-up costs and associated legal liability. The requirements also require knowledge of the geo-environment, in order to predict and improve the performance of detection systems and in the provision of terrain information and situational understanding of the battlespace environment. Knowledge of sediments and sediment transport and the characteristics of aquatic vegetation are also important for the detection of buried and underwater ordnance and the performance of sensor systems, including their use for hydrographic surveys and the maintenance of waterways.

Table 1. Summary of Challenges and needs

Medical Challenges & Needs	**US Navy and Army Challenges & Needs**
Goal: Improve health	***Goal: Ensure safe passage & environments***
Reduce number of poor images	Reduce number of poor images
Reduce number of false contacts	Reduce number of false contacts
User friendly systems & interfaces	User friendly systems & interfaces
Reduced operator dependence results	Reduced operator dependence results
Higher frequency and wider bandwidth transducers	Higher frequency and wider bandwidth transducers
Improved tissue characterization	Target, including sediment, suspended sediment and aquatic vegetation, material characterization
Imaging through bone	Imaging through sediments, turbid water & vegetation
Targeted contrast agents	Improved knowledge of target properties
-	Capitalization on existing data
Quantitative perfusion with contrast agents	-
True 3D blood flow imaging	-
-	Improved underwater communications

The applications of bioacoustics in medicine and military/ environmental sensing are the basis for multi-billion pound commercial industries that support and develop sophisticated technologies. They are in some senses mature, but looking for new approaches. At the other end of the field of applications many smaller industries are also using bioacoustics and may already have developed approaches that could usefully be adopted by relatively more mature technologies. Research at the University of Leeds into the use of sound for the visually impaired has allowed blindfolded people within an open space (floor of a mosque) to navigate to a sound source using chirps (slowed down, and at an audible frequency). Whilst the research has allowed the university to develop an acoustic walking cane for visually impaired people (a multi-disciplinary project extending from basic research to constrain the concept to design and testing for production), much of the Basic Science may be applicable to areas such as medical or military/ environmental sensing. It is thus necessary for acoustic scientists from a wide range of industries or experience to meet and present results and ideas in a common forum. It is also important that they are explicit, not only in clarifying what they have achieved, but what gaps or questions still need to be addressed – hence the need for this workshop.

2 The state of Our Current Understanding of the Basic Science of Bioacoustics

John Fay[1], Chris Clark[2], Patrick W. Moore[3] and James A. Simmons[4]

[1]Office of Naval Research – Global, US Navy
[2]Electronic & Electrical Engineering, University of Bath
[3]Biosonar Program Office, Space and Naval Warfare Systems Center, San Diego, California
[4]Biological and Medical Neuroscience, Brown University

What do we know about the signals animals use and the cognitive processes they use to acquire knowledge about their environment?

With regard to performance, current radar and sonar systems rely on and are limited by standard physical properties: power transmitted (source level), power reflected by target (target strength), signal attenuation of the media between transmitter and receiver (transmission loss), background noise level (ambient noise) and receiver performance. Clearly, in reviewing what elements of bioacoustics may be utilised in solving the limitations of engineered systems, it is important to identify those characteristics of biological systems that are physiologically controlled or are constrained by behaviour. It is thus important we define what we know about the signals animals use and the cognitive processes they use to acquire knowledge about their environment. Research programmes that highlight the functioning of animal systems are important in order to provide clues to the prioritisation of research into engineered systems. Of particular importance are those identifying the novel features of transduction and processing used by echolocating bats and dolphins in relation to man-made methods.

The wideband, frequency modulated biosonar system used by bats reveals a whole cascade of differences in basic design having little or no overlap with engineered systems in transduction, waveform representation, signal-processing, or display. System elements bats have developed are notable for several reasons. Firstly, in its capacity as a sonar receiver, the bat's auditory receiver utilizes a more radical concept of parallel processing than anything manifested in even the most advanced man-made systems. Secondly, the organization and interplay of time-domain and frequency-domain elements used by bats yields a higher degree of systems integration than would be expected from examination of any of the elements in isolation. (It is worth noting, however, that knowledge of this system can be exploited to design unconventional man-made systems, but not if the goal is merely to emulate animal performance with conventional digital signal-processing devices.) Thirdly, the efficiency of object imaging and classification in echolocation derives from parallelism inherent throughout the entire system, not just from a particular choice of target features, which implies the need to design systems from the ground up.

The most familiar behaviour of echolocating big brown bats is aerial interception of flying insects, and by slowing down recordings, it has been shown how successive sounds in the pursuit sequence of frequency modulated sonar signals become shorter in duration and faster in repetition-rate as the bat approaches the target. The bat's external ears act as receiving antennas. When viewed from the side, these are seen to be approximately obliquely truncated horns whose tapered cross-section aids in impedance matching from free-field sound to the eardrum. Transduction takes place inside the spiral cochlea after sound is mechanically coupled from the eardrum to the cochlear fluid by the middle-ear system. Inside the cochlea, the spiral organ of Corti filters the frequency modulated sweeps into a succession of frequency segments. Each of the thousand or so bandpass filters in the cochlea has level-dependent gain. Signals being transduced at different amplitudes nevertheless have constant phase characteristics. Analyzing the reception and processing of biosonar echoes is done in two passes- first, in terms of signal-processing, and, second, in terms of neural circuits. The best way to illustrate the temporal organization of the bat's cascade of representations is with animation of an auditory model.

Recent bat cochlear research has provided an approach that indeed aspires to implement bat neural processing using fundamental principals of modern chip design to implement multiple (hundreds) of filter channels and million-gate Field Programmable Gate Arrays (FGPA) signal processing. Modelled bat ears and a synthetic bat cochlea have been used to explore bat echo-perception. This research has attempted to model the low-speed, massively parallel world of bat neurophysiology using high-speed serially processed digital architecture while clearly attempting to implement what is currently known about how bat ears work. Signal processing is now being pushed "…beyond single DSP capabilities" implementing a neuronal (threshold-spiker based) approach to target detection. Results from this exercise to build a bat cochlea reveal the complexity of modelling a neurological system. Insights into recent research required to actually implementing a working bioacoustic detector that can guide a robotic device will help drive future efforts. In addition, future designs that overcome the limitation of standard serially processed digital data, as currently implemented in most digital computers, must be discovered if we are to match biological systems. The application of FGPAs appears to be a useful and productive approach.

In dolphins, different acoustic fat bodies have been identified for definition of high and low frequencies. Although the cochlea has a basic mammalian shape there is variation in basilar membrane (supported by lateral structural elements), compared with humans its thickness and width are much greater and there is a higher neural density. Dolphins & whales use high repetition rate signals with a large frequency range and can be loud- some can reach 228 dB for echolocation clicks (it has been suggested that dolphins stun prey using jawclap and killer whales using "bangs" or low-frequency signals). In echolocation signal generation, cat scan studies have identified the probable source of sound in cetaceans: the dorsal bursae in echolocation and the entire spiracular cavity in prey debilitation.

The ability of cetaceans to determine physical properties of remote objects has been demonstrated by experiments in which dolphins determined wall thickness of metal mine-like objects. A Biosonar Measurement Tool (BMT) concept was used to collect detailed free swimming dolphin data regarding bioacoustic emissions and echoes, 3D Positional Data / Hunting geometry, to conduct analysis of dolphin strategies, and to allow animal signals detection by whistle. Laboratory analysis of dolphin strategy was undertaken using Virtual Reality Modelling Language (VRML). The click characteristics of the dolphins were notably different. Based upon the click taxonomies developed largely by teams led by Houser and Au using amplitude and frequency characteristics, categories were reduced to: wideband, low frequency unimodal, high frequency unimodal, bimodal and multimodal. Features include -3 dB bandwidth, peak frequency, and number of peaks within this. A study of variance (based upon comparison of proportional click use following modified Freeman and Tukey transform - arcsine) showed no change between "search" and "acquisition", and strong differences in click type usage.

Cetacean studies such as these have extended our knowledge of Bioacoustics though many questions remain unanswered (for instance, we still do not know if dolphins actually form "images" of targets they echolocate). However, some aspects of the research described above has led to the development of Biomimetic Synthetic Aperture Sonar (BioSAS©) target imaging algorithm patented (US. Navy) which runs in near-real time. BioSAS© features images of buried objects are sensitive to interaural cross-correlation of echoes from various target points (cross-correlation images).

In summary, it is clear that bats and dolphins provide an excellent paradigm for developing models of biological signal detection, localization, classification and categorization. There is a well-developed methodology for investigating the bioacoustic capabilities of these animals. The bat and dolphin provide a well-bounded bioacoustic problem and demonstrate the solution of that problem thereby proving that biological sonar-based recognition of multiple target properties is feasible. The study of biological systems continues to inspire bioacoustic designs by revealing properties of animal performance that lead down a development path that seeks to include more of the mechanisms that we can identify from the neurobiology of echolocation and from the performance of bats and dolphins. We also note that more work is needed in order to duplicate dolphin and bat sonar biosonar performance in hardware. Engineering state-of-art in signal processing hardware has advanced to the point where it now appears that functional modelling of simi-real time processing resembling the biological system is possible. FGPA and very large-scale integrated chip technology advances have put this capability in the hands of the bioacoustic researcher. Bio-inspired engineering should continue to be calibrated against the biological system performance being modelled in an attempt to fully understand the underlying physical properties of that system.

3 The conceptual basis for Bioacoustics-based engineered systems

Mike Rothe[1], Gordon Hayward[2], Peter Jackson[3], Laurie Linnett[4], John Rees[3] and Andrea Trucco[5]

[1]SPARWAR Systems Center San Diego, US Navy
[2]Centre for Ultrasound Engineering, University of Strathclyde
[3]Geophysics and Marine Geoscience, British Geological Survey
[4]Fortkey Ltd.
[5]Department of Engineering, Biophysics and Electrics, University of Genoa

Addressing the question of how bioacoustics signals can meet human information needs, what will be the characteristics of an engineered bioacoustics system?

In our current efforts to apply bioacoustics knowledge to meet technology and engineering requirements we need to remember that nature has been a wellspring for inspiration and invention since humans first marvelled at its many creations. In fifteenth-century Italy, Leonardo da Vinci, was the first to seriously study the way birds flew. He sketched bird wings and muscles and his notebooks contained many drawings and descriptions of birds in flight. He modelled his first flying machines after what he saw in nature. Unfortunately, this biomimetic approach to the study of nature failed Leonardo as it assumes an understanding of the underlying principals of the phenomenon under study. Leonardo's models never flew because he failed to realize that humans lacked the underlying biological mechanisms of flight. Later attempts succeeded as they were based on a foundation of understanding the underlying principles of aerodynamics. The successful flying machines we see today are the result of bio-inspired engineering- and so it should be with the study of nature's implementation of animal bioacoustics. We need to strive to understand the underlying physical and engineering principles as they are applied in nature to the creation of animal bioacoustics. Why is it that bats can navigate and catch evading insects among dense clutter and other bats and how it is that dolphins can detect and discriminate differences between targets and find buried fish all using only acoustics?

3.1 New approaches to Transducer design, Receiver design and Signal Processing

3.1.1 Advances in transducer design

In consideration of the state of the art with regard to transducers and issues currently facing transducer-manufacturing ultrasound frequencies are moving higher and higher in an attempt for better resolution and 3D image reconstruction. Consequently new transducers need to have higher bandwidth and better over all efficiency. Perovskite single crystals may be one answer to higher bandwidth and better coupling, however, they are hard to grow and are very expensive. Multi-layered composites and inversion layer transducers are increasingly being considered as alternatives. Multilayer piezoelectric composites present a viable approach for the manufacture of low frequency sonar transducers and layers can be either uniform or non-uniform in thickness for production of selected frequency response. Transducer design has moved far in the past several years due in large measure to the push from medical ultrasound applications. Bioacoustic applications would require transducers with extremely wide bandwidth (80-90 kHz) with centre frequencies between 30-120 kHz. For air-mediated bat signals the impedance matching from transducer material to air results in remarkable losses for piezoelectric and composite materials and traditional ultrasonic speakers are limited in source levels. In water, biosonar source levels approaching 230 dB have been measured for dolphin signals. Although advances in composites and crystals transducers for medical ultrasound have been made, developments in pneumatic driven transducers should be pursued for bioacoustic applications. Bats and dolphins both produce sound using pneumatics and an alternate production mechanism should be explored for increased bandwidth, source levels and lower energy requirements.

3.1.2 Advances in Receiver design

Research has demonstrated that bioacoustic systems show excellent spatial filtering and that echolocation signals contain signals that have wavelengths that are both much shorter and longer than the receiver aperture. This questions whether it possible to achieve a good spatial directivity by using a receiving aperture that is shorter than the wavelength. In attempting to design a "good spatial filter" using a short receiving aperture of omni-directional sensors, a bioacoustically-inspired design using an eight-sensor array with a 12cm aperture has been generated. A wideband beam formed by applying a Finite Impulse Response (FIR) filter to each sensor has recently been implemented in combination with the use of a statically based approach to derive weighting functions to the windowing of the filters to approximate the desired beam patterns. Using a traditional least-squares and a newer simulated annealing approach (based on a stochastic optimization technique followed by a local descent method for unconstrained minimization - developed out of applications in artificial neural networks) recent work has attempted to produce desired beam patterns via manipulations of the weighting function of the FIR filters. Through various experiments and the use of multiple filter taps the objectives of these experiments were met and concluded that sensor arrays using tapped-delay lines provides considerable potential for development. The next logical research step would be to implement and derive bat or dolphin receive beam patterns using a minimum of two wideband sensors. However, a much better understanding of the complexity of the bat ear and the multiple delays introduced by the variations in the surface of the pinna and the tragus need to be better understood initially. Additionally, the effect of sound entering the lower jaw and penetrating the various fat channels that comprise the dolphin ear is a complete mystery at present.

3.1.3 Advances in Signal Processing

Looking towards new approaches to signal processing we need to explore the chirp signals used by both bats and dolphins. New tools, or novel use of conventional methods, must be developed. One such technique is the use of fourier extensions for practical chirp analysis. Fractional fourier analysis can be utilised to refine and sharpen the separation of the frequency components of signals for improved analysis. These new time-frequency (t-f) analysis techniques should allow greater insight into the fine signal structure of the animal signals and help further understanding of the complex cues used by animals to perform their outstanding bioacoustic feats. So far these t-f approaches have allowed the delineation of multi-component chip structure in both bat and dolphin signals, which seem to have similar near-linear (quadratic phase) down-chirps, overlapping in time and frequency. It should be stressed that these animals appear to be "painting their environment with phase". It is extremely important that we further explore phase disparities to give us strong cues about how animals "image" their acoustic environment. Phase detection and discrimination has been explored in bats and are known to play a major role in the bat's echolocation system. However, similar experiments with dolphins have not been conducted and the role of phase (or range jitter) has never been adequately explored. In summary, new approaches to the application of t-f processing and the exploration of chirp signals should be pursued with great vigour.

4 What approach should we use in developing bioacoustics?

Based on a discussion involving all contributors, convened by John Rees[1]

[1]British Geological Survey

Addressing the questions: what are the limitations of engineered systems in relation to animal systems and should we try and copy nature, or primarily be inspired by it?

The presentations described in Section 3 were taken as the basis for a facilitated discussion related to the two questions above.

4.1 Features of animal acoustic systems and limitations of engineered systems

There are several features of animal acoustics that cannot be approached within human-designed systems. We need some of the tricks from natural systems since animal acoustic 'technology' is 50-50,000 times better than human. Much of the discussion focused upon the abilities of bats to sense their environment. Their capabilities are outstanding. They manage 0.2mm resolution using 100kHz transmit pulses and increase (PRF) to fill the time space and are able to achieve $\lambda/10000$ resolutions. There was some discussion about how they perform such resolution. We use vernier scales to improve measurements perhaps a similar trick can be used in ultrasound. It was suspected that in bats single molecules and proteins perform crucial tasks.

The acoustic techniques of dolphins are recognized as being different, and appear to be more simplistic than those of the bats; however their capabilities are no less impressive. Dolphin processes may be easier for us to adapt for our own technologies if we knew more about how they did it.

In considering what features of animal systems may offer us clues as to where new research should be focused, as far as we know, no animal uses sinusoids. It is likely that cetaceans and bats all look for changes in returns from multiple signals and that one of the key changes they look for is in phase. To date such changes have been little investigated in human systems.

Another general difference between animal systems and engineered systems is that we use single frequencies while animals use many. Animals are also able to utilise frequency dispersion. Improvements in resolution of engineered systems to date have been made by going up in frequency but, for many reasons, this trend cannot be continued. From a medical viewpoint it would be valuable to gain information about the elastic properties of tissue and get beyond the barriers imposed by the frequency.

The other area in which animals have much greater capabilities than us is in angular resolution; imaging is more than just a range issue and lateral resolution is equally important.

In addressing the shortcomings of engineered systems it seems that we adopt very simplistic approaches, such as assuming a single speed of sound 1540m/s, for all tissue types in clinical applications. This is over-simplistic and clearly is likely to have shortcomings. It is likely that many of our processing techniques are extremely unsophisticated and that some approaches, for instance binaural processing have been neglected. From a signal-processing standpoint, we should avoid complex computational methods and instead use massively parallel simple non-recursive and non-time specific methods. Finally, in signal generation it is important to note that the current generation of ultrasonic transducers is not in any way bio-inspired. Transducers tend to be developed using computer modelling techniques since experimental development methods are much too expensive.

4.2 Bio-inspired rather than biomimetic approach

There is a growing awareness that copying bats and dolphins may not be the best approach to developing new technologies. As scientists we should implement the techniques used by bats and dolphins using our own methods. There still remains some debate as to whether copying may be a useful strategy to try first, to try and find what ‘tricks’ animals use. However, there are concerns that animals may not be using the most efficient techniques for engineered solutions and whilst their capabilities far outreach ours we should be wary of spending too much resource in reproducing a system that has been adapted for evolution for a very specific purpose and which may not be a key goal for us. There is general agreement that implantation of techniques used by animals may go some way but a biologically *inspired* approach could well be more fruitful. If resources for development of a research program were plentiful, it would nevertheless be useful to try and copy animals with a view to understanding the tricks used by bats and dolphins- if nature can do it, surely we can too.

Biomimetics becomes a material development and manufacturing problem as we try to develop materials capable of performing the same function and levels of efficiency as those used in nature. To progress in this field, new technologies would be required including developments in micro engineering, new simulation tools, and new types of programmable arrays.

In concluding this section it is clear that many of the challenges we face are great. However, it is worth remembering that in attempting to develop new technologies we should not loose heart at the size of the challenge we face. Even incremental improvements in technology would be of enormous value to society.

5 Science and technology gaps

Bob Allen[1], Les Atlas[2], John Fay[3], Matt Geen[4], Jeff Haun[3], Gordon Hayward[5], Ivor Kirsteins[6] and Tengiz Zorikov[7]

[1]Institute of Sound and Vibration Research, Southampton University
[2]Department of Electrical Engineering, University of Washington
[3]Office of Naval Research – Global, US Navy
[4]Systems Engineering & Assessment Group Ltd.
[5]Electronic and Electrical Engineering, University of Strathclyde
[6]Naval Undersea Warfare Center, US Navy
[7]**Institute of Cybernetics, Georgian Academy of Sciences**

Identifying research needs and priorities

5.1 Basic Science

Air and water based bio-acoustic systems have developed very sophisticated means of object detection, location and characterisation. The technologies involved in the generation, reception and processing of acoustic signals go way beyond man's current understanding. Current technology drivers in most scientific, military and industrial fields include increasing resolutions, lowering power consumption and improving material assessment and characterisation. Existing solutions often result in current technologies merely being driven harder, but new, novel technologies can be developed from a fresh view of the way bio-acoustic systems solve similar problems.

How bats and dolphins achieve such high levels of object detection, location and characterisation has been the focus of much research. One aim being to develop similar, 'bio-mimetic' systems, but it is still unclear the effort that is required to approach the capability of bio-acoustic systems. Recent experiences suggest that our research should be 'bio-inspired' and investigate the way in which energy is delivered to and returned from the source of investigation. This will require a core research of the tools / techniques used routinely by nature that hitherto have not been embraced by man. Key challenges for a new approach is breaking the half wavelength barrier that currently limits spatial resolution, and mankind would be taken to a new plateau were this achieved.

Knowledge gaps that could be addressed by fresh research include:

5.1.1. Signals used in natural bio-acoustic systems

5.1.1.1. What are the different signals, chirps, clicks etc used for a) detection, b) ranging / sizing, c) location, and characterization?

5.1.1.2. How does the character of signal used relate to and how is it adapted or processed to undertake functions in 5.1.1.1.?

5.1.1.3. Can a standardised suite of signals be developed for application to functions in 5.1.1.1.?

5.1.2. Effect of propagation medium on signals used in natural bio-acoustic systems.

Phase information is often ignored; if included in new processing techniques, what information can be gained about signal dispersion through different media.

5.1.2.1. How do bio-acoustic systems process information and can new bio-inspired techniques be developed?

5.1.2.2. Can a standard signal processing toolkit be developed for application to functions in 5.1.1.1.?

5.1.3. Signal generation/detection processes and technologies.

5.1.3.1. Can current transducer technologies generate / detect the signals required?

5.1.3.2. Can existing technologies be used in new designs to generate / detect signals required?

5.1.3.3. What are the newly emerging materials and how can these be exploited?

5.1.4. Signals used in natural bio-acoustic systems

5.1.4.1. Can adaptive arrays be developed by exploiting new technological advancements with improved a) angular resolution, b) spatial resolution and c) dynamic range?

5.2 Engineering

In analysis of engineering it is useful to identify the major research needs and what gaps exist in engineering.

5.2.1. Underlying basic research needs:

Two key areas were identified:

5.2.1.1 *Biomaterials*- is an evolving area and strategically important research is being undertaken in terms of the behaviour of biological sensors and actuators, and also as a basis for the development of bioacoustic methods of sediment classification and ultrasonic imaging.

5.2.1.2 *Neuroscience of Cognitive Processes*- The fusion of information from bioacoustic sensors for echolocation and material characterisation based upon current understanding of the ways in which this is achieved in bats and dolphins is of particular interest.

5.2.2. *Gaps in Engineering*

5.2.2.1 *Adaptive Non-linear Systems Analysis*- This area requires considerable development in order to Model and investigate the complex dynamic processes involved.

5.2.2.2. *Biomimetic Mechanism Fusion*-The marriage of state-of-the-art knowledge in Biological, Physiological and Biochemical Mechanisms with Electromechanical Mechanisms was considered to be essential to biomimetically advance engineering mechanisms, but also for applying modern engineering tools to investigate and model biological systems.

5.2.2.3. *Hybrid Modelling*- Modelling is currently limited by the techniques available which tend to be compartmentalised. For example, finite element modelling (FEM) is currently limited in scope and advances are necessary to model the complex problems associated with the bioacoustic areas of interest.

5.2.2.4. *Behaviour of Biomaterials*- Measurement techniques are required for the bio-viscoelastic materials and for particulates and sediments.

5.2.2.5. *Information Fusion*- Techniques for integrating the data from bioacoustic sensors are required, together with appropriate methods of presenting the information for the end-user.

5.3 Information Processing

As seen in the presentations (Appendix 3), it is clear that for short-range (less than about 100m distance) problems in acoustic echolocation, dolphin and bat performance greatly exceeds current human engineered systems. The clarity of dolphins' acoustic underwater view and the information processing density of bats' range estimation system are extreme examples of the gaps between what is achievable and what computer information processing has so far achieved. In spite of years of effort, this gap is still large and can only be closed via a focused effort. Similar conclusions are reached when comparing the performance of artificial speech recognition and auditory scene analysis systems against humans. The current state of the art of automatic speech recognition system under ideal conditions, single speaker with no noise, still performs about an order of magnitude worse than a human.

5.3.1. Specific problems with the current state-of-the-art in sonar, radar, and related areas

5.3.1.1. We cannot resolve distances and angles with anywhere near the performance of echo locating animals.

5.3.1.2. The signal processing concepts used in bioacoustic systems to achieve directivity as in interferometry, traditional beamforming and adaptive beamforming are not known.

5.3.1.3. The way phase information is exploited in bioacoustic systems, mainly in object detection and identification is not understood.

5.3.1.4. Statistical-based signal processing and pattern recognition approaches by themselves do not seem to be able to solve the problem.

5.3.1.5. We cannot design and/or build transducers or arrays with anywhere near the performance and, most importantly, environmental adaptability of animal binaural systems.

5.3.1.6. While contributing to scientific understanding, our attempts to model animal systems has not yet provided direct improvement to engineered systems.

5.3.1.7. The general or overall form of signal processing used by animals in lower-level echolocation and related tasks is fairly well understood, as expressed as block diagrams. However, higher-level processes such as cognition are not well understood.

5.3.1.8. Formal mathematical models representing the functionality of animal signal processing at both the low (cochlear) and high (cognitive) levels have not yet been developed. This is analogous to the difference between watching a bird fly while observing a bird's wing versus discovering Bernoulli equations, which govern airfoil lift. We do not yet have the "Bernoulli equations" which explain why animal systems do so well.

5.3.1.9. Animals use signal processing approaches, which are distinctly different from human-engineered systems. For example, human-engineered processing usually assumes time-invariant systems; animals' systems often sidestep this assumption.

5.3.1.10. Aside from the observation that animals can indeed acquire resolutions at substantially small fractions of a wavelength, performance bounds for the tasks (detection, range and angular estimation, and classification) presented to these animals, are unknown. Some examples of possible applicable performance bounds are: Cramer-Rao, Ziv Zakai, Barankin, and Minimum Description Length (MDL) bounds.

5.3.1.11. The mechanisms ruling the adaptation of pulses emitted by bioacoustic systems over time is not known. On what are they based and what is the aim?

5.3.1.12. Some bioacoustic systems employ multi-frequency (chirp) transmission. What means or what non-linear processing "technique" exploits this information?

5.3.1.13. The statistical formulations used in conventional manmade systems are indeed advanced, yet there is a serious mis-match between the current models, which explain animal performance and the formal needs or conditions of these statistical formulations.

5.3.1.14. While the above examples and discussion focused on acoustic range and location performance, similar challenges also apply to radio-frequency systems such as radar systems.

5.3.2. Possible Near-Term Future Opportunities

We need better understanding of current scientific results and their impact on possible engineering implementations and computer algorithms. Ideally, since we know such solutions are indeed possible, we would like to demonstrate performance, which is equivalent to that seen in animal studies. Some examples of key challenges include:

5.3.2.1. Detecting, classifying, and localizing man-made objects in difficult and changing environments.

5.3.2.2. Identifying unknown threats in difficult and changing environments.

5.3.2.3. Mapping the bottom of the ocean or other key areas.

5.3.2.4. Pipeline route mapping through complicated areas.

5.3.2.5. Combining multiple sensors and modalities, via collective intelligent signal processing, into solutions for above challenges.

Clearly, performance metrics need to be chosen which can best assess comparisons between animal and human-engineered systems. These metrics need to be valid for users of systems, which meet the above challenges. Meaningful standard data sets for these comparisons are essential.

5.3.3. Plan to Achieve these Opportunities

In order to meet these challenges, these are the main directions of change from conventional approaches:

5.3.3.1 New signal representations are needed for human engineered systems. For example, while there is evidence that local (in time and frequency) monaural phase differences are important, if not key, for bat echolocation, this part of the signal is ignored by current sonar and radar systems or indeed medical systems. Moreover, the environmental adaptability of animals' systems strongly suggests that invariant parts of signals have not yet been found or utilized.

5.3.3.2. An overview of the systems mimicking bioacoustic systems designed till now is needed, as is a "consensus report" on their real advantages and drawbacks, with respect to traditional systems.

5.3.3.3. An attempt to introduce bioacoustic concepts into existing traditional acoustic systems (in underwater/ medical/ air-borne applications) is necessary to establish attainable performance improvements.

5.3.3.4. More advanced mathematics and signal processing methods need to be made available and accessible for animal modellers. Conventional views of stationary frequency analysis and linear time-invariant filtering are insufficient as tools for formal mathematical modelling of animal systems.

5.3.3.5. Modelling and simulation of animal systems must progress to the point where formal mathematical models are available to complement the statistical formulations successfully used within conventional sonar and radar systems. Block diagrams, no matter how clever, are not sufficient for merger with the advanced techniques used in current sonar and radar systems.

5.3.3.6. Better understanding of the higher-level animal and human cognitive processes, e.g. echo features used and the pattern recognition “algorithms” is essential in order to replicate the performance of bioacoustic systems. It is not adequate to merely understand the lower level functionality of the cochlea or transducer components. This would be like trying to understand how a manmade sonar works by reverse engineering only the hydrophone and analog-to-digital sampling system and ignoring all the signal processing and pattern recognition algorithms that the sonar system uses at the higher levels.

5.3.3.6. The performances of bioacoustic and manmade sonars doing similar tasks must be accurately quantified and bounded. In other words, how well would a dolphin or bat sonar actually do in hunting mines in clutter at ranges of a few hundred meters when compared against a manmade sonar? There has to be an “apples to apples” comparison to determine the best achievable performance that manmade sonar could attain even when using bioacoustic signal processing techniques.

5.3.3.7. As described above, it is important to provide the research community with meaningful and challenging standard test sets for identification and classification. This test set should be focused enough to permit various teams to achieve results in time for a next workshop, and should be broad enough to include different materials. It can include data from both a tank test and an open water test. This data needs to be distributed to appropriate researchers with an expectation of a follow-up workshop presentation and submission of results to refereed journals.

5.3.3.8. Although we have focused on the sonar problem, we feel that the ideas discussed above apply directly to the medical, biomedical, and other applications. We have deliberately omitted detailed discussions of these applications because they will be treated elsewhere in the overall report. These applications are clearly central to the workshop. We feel, however, that consideration of these applications and related issues will serve to reinforce the argument made here for further research opportunities in Information Processing. Possible Funding Sources include: ONR, DoD MURI, NAVSEA, or other codes, European Commission, NATO and UNITA.

5.4. Applications

In assessing whether bioacoustics signals, and the approaches animals employ for interpretation, can be used to meet human needs, it is important to recognise that *both* are needed.

Suggested glossary:

- Bio-mimetic: imitating biological functions, close to the way that the animal works
- Bio-inspired: borrowing techniques from biological systems in order to improve human technology
- Bio-masking: making a human signal sound like an animal signal, in order to communicate covertly. A short human signal may be embedded in a much longer imitation of a biological signal.

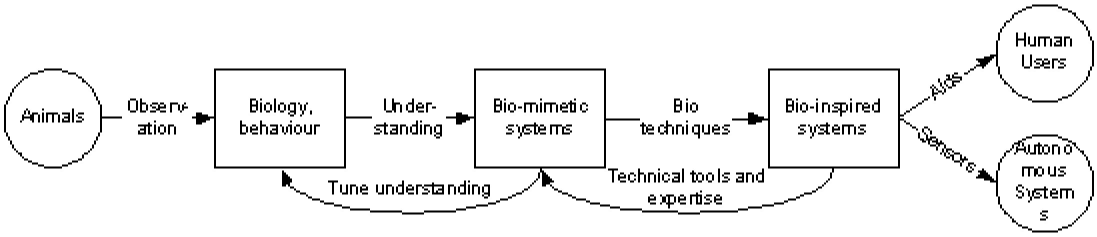


Figure 0-1 A Bio-Acoustic "Tool-Flow"

Materials science is key to bioacoustics, especially in replicating the transducer sensitivity.
"Lambda barrier": detecting object properties at less than the wavelength of sound. Animals can do λ/10,000: we would be pleased with λ/10!

5.4.1. Defining an effective research agenda

Some important points:

5.4.1.1. Animals seem to have a better "frame of reference" than autonomous systems can manage: how?

5.4.4.2. Human automatic speech recognition is still poor compared to real biological humans

5.4.2. Key techniques needed

5.4.2.1. Use of relative phase

5.4.2.2. Frequency agility

5.4.2.3. Separation of multiple sound sources (e.g. multiple people talking in a room) may use modulation analysis (c.f. DEMON)

5.4.2.4. Transducer technology: move towards micro-machined, on-chip arrays, with processing electronics incorporated

6 Summary

The review of the bioacoustics and its application to engineered systems undertaken at the workshop and summarized here gives a good picture of present status of science in the field and provides some useful pointers toward where the gaps in engineered systems may be which could be exploited in future technological development.

The applications of acoustics are seen across almost the whole spectrum of human technologies (medical and military uses are given as examples in section 1). Such applications result from a vast amount of research, much of it over the last 50 years during which time enormous advances have been made in our use of acoustic tools across a wide range of technologies.

However in the field of bioacoustics, despite the efforts of many researchers (and the related costs of their funders) inspired by the clear potential to develop similar capabilities to those of bats and dolphins, relatively little progress has been made. In many ways many parallel technological developments have all hit the same brick wall; singly and jointly they have failed to gain a basic understanding of the way in which bats and dolphins can resolve targets much smaller than the wavelengths they use and how they can resolve the physical characterstics of targets solely using acoustics.

What we have gained, however, is a view of the animal world (Section 2) that gives us clues about how animals use acoustics. Whilst our understanding of the relationship between physiology and acoustic systems is rudimentary, it would appear likely that animals use:

- Chirps
- Multiple signals
- Multiple frequencies
- Frequency dispersion
- Phase
- Parallel simple non-recursive signal processing.

These are all features that have been relatively little-explored engineered systems to date.

Where there may be some scope for optimisim is that recent developments in transducer, receiver and signal processing (Section 3) would suggest that a reassessment of how technologies may benefit from bioacoustics is very timely. It is important, though, to ensure that we do not become distracted by focusing too many resources on biomimetics, but on developing techniques and systems based on manutactured materials and human designed systems (Section 4).

On the basis of the above, many areas of research are required or desirable in order to ensure a technological breakthrough (Section 5). Individuals or consortia will need to consider carefully how to prioritise and schedule these. What is apparent from the number of research questions, is that no single research initiative can expect to tackle more than a few issues in a project. The questions are owned by the global scientific community; answering them requires collaboration, avoidance of competition (and reproducing the wheel) and a willingness to communicate ideas. It is thus important that researchers have the opportunity to discuss developments and constraints openly in the future. As a result it may be seen that the Bioacoustics Workshop held in North Berwick in 2004 will be seen as the first of a series of events that will enable acoustic scientists jointly to make a major advance in the field.

Appendix 1 – Agenda

Tuesday, May 4, 2004

Introduction

08:00-09:00	Final Registration
09:00-09:10	Welcome and administrative notes - *John Rees*
09:10-09:25	Workshop format and objectives - *Bob Kennedy*
09:25-09:45	Participant introductions

Session 1: Defining challenges and needs *(Chairperson – Nick Langhorne)*

Objective: Review the challenges and current approaches to describing environments using acoustic or bioacoustics, and identify real-world needs that are not currently met with existing technologies.

09:45-10:05	Medical challenges and needs – *Norman McDicken*
10:05-11:15	Military and environmental challenges and needs – *Rob Simmons (US Navy), Bob Kennedy (US Army Corps of Engineers) and John Rees (British Geological Survey)*

--*break*—

Session 2: The state of our current understanding of the basic science of bioacoustics *(Chairperson – John Fay)*

Objective: Define what we know about the signals animals use and the cognitive processes they use to acquire knowledge about their environment.

11:45-12:15	Results of recent research on bats - *Jim Simmons*
12:15-12:45	Overview of dolphin bioacoustics – *Pat Moor*

--*Lunch*--

Session 3: Defining the engineering state of the art *(Chairperson – Mike Rothe: Reporter – Laurie Linnett)*

Objective: Review current efforts to apply bioacoustics knowledge and technology to meet engineering requirements.

14:00-14:30	Bat cochlear research - *Chris Clarke*
14:30-15:00	Signal processing applications – L*aurie Linnett*
15:00-15:30	Advances in transducer research –*Gordon Hayward*

--*Break*—

16:00-16:30	Exploiting very short arrays –*Andrea Trucco*
16:30-17:00	Biodynamics and cognition – *Bob Allen*
17:00-17:15	Discussion recap – Day 1
18:00-18:30	Welcome – Lord Provost, East Lothian

18:30-20:00 Workshop Dinner

Informal Evening Seminar

20:00-22:00 Participant presentations and open discussion
Matt Geen
Paul Doust
Dean Waters
Dick Altes (submitted via email)

Wednesday May 5, 2004

Session 4: Developing the conceptual basis for an "Acoustic Spectrometer" (Chairperson – *Peter Jackson: Reporter – Tom Anderson)*

Objective: Seek consensus on the feasibility and attributes of an "acoustic spectrometer"

09:00-09:20 Collaborative research efforts for the UK – *John Rees*
09:20-09:40 Human assistance research – *Dean Waters*

09:40-10:40 Facilitated Discussion – *John Rees (Reporter – Tom Anderson)*

Theme: Can bioacoustics signals, and the approaches animals employ for interpretation, be used to meet human needs? What are the desired characteristics of an "acoustic spectrometer" and what would be our expectation of its performance?
--*Break—*

Session 5: Defining an effective research agenda

Objective: Identify gaps in our understanding of the science and technology of bioacoustics by comparing and contrasting bioacoustics systems and engineering systems, and seek consensus on a research agenda designed to close these gaps.

11:00-11:30 Biological systems – *Les Atlas with input from Jim Simmons, Dean Waters, Chris Clark and others*
11:30-12:00 Processing bioacoustics signals – *Ivars Kirsteins with input form Laurie Linnett, Dick Altes (submitted in absentia), Andrea Trucco, Walter Zimmer and others*
12:00-12:30 Transducer design and performance – *Gordon Hayward with input from Paul Doust, Bob Allen and others*
12:30-13:00 Bio-mimetic sonar: results achieved and the road to improvement –*Tengiz Zorikov with input from others*

--*Lunch*--

14:00-15:30 Group Discussions (*Chairperson: Matt Geen- Synthesizer: Bob Allen*)

Theme: Defining an appropriate research agenda that addresses gaps in science engineering information processing and application procedures (Discussion Leader/Reporter)

Group 1 - Basic science (*Jim Simmons// Jeff Haun*)
Group 2 - Engineering (*Bob Allen/Mardi Hastings*)

Group 3 - Information processing (*Les Atlas/John Fay*)
Group 4 – Application procedures (*Matt Geen/Tom Anderson*)

--*Break* --

(Preparation of group summary reports)

Workshop Conclusion

16:00-17:15	Presentation of discussion group summaries – *Bob Allen and Group Reporters*
17:15-17:30	Workshop summary and closing remarks – *Bob Kennedy*
17:30	Adjournment and departure

Appendix 2 – Workshop Participants

Allen Robert
Institute of Sound & Vibration Research
Southampton University, UK.
Anderson, Thomas
Medical Physics Dept.,
University of Edinburgh, Scotland
Atlas, Les
Department of Electrical Engineering,
University of Washington, Seattle, WA. USA.
Clark, Chris
Electronic and Electrical Engineering,
University of Bath, UK.
DeVaud, Frederic
Electronic and Electrical Engineering,
University of Strathclyde, UK.
Doust, Paul
Blacknor Technology Ltd., Portland,
Dorset, UK.
Fay, John
Biosciences Dept., Office of
Naval Research Global, London, UK.
Geen, Matt
Systems Engineering & Assessment
Group Ltd., Beckington, UK.
Gunn, David
Geophysics & Marine Geoscience,
British Geological Survey
Keyworth, UK.
Hastings, Mardi
Office of Naval Research,
Arlington, VA. USA.
Haun, Jeff
Biosciences, Office of Naval Research
Global, London, UK.
Hayward, Gordon
Electronic & Electrical Engineering,
University of Strathclyde. UK.
Jackson, Peter
Geophysics & Marine Geoscience,
British Geological Survey,
Keyworth, UK.
Kennedy, Robert
European Research Office, Engineer
Research and Development Centre,
London, UK.
Kirsteins, Ivars
Naval Undersea Warfare Center, Newport
Rhode Island, USA.
Langhorne, Nick
Biosciences, Office of Naval Research Global,
London UK.
Linnett, Laurie
Fortkey Ltd., Elvingston Science Centre,
East Lothian, Scotland.
McDicken, Norman
Medical Physics, University of Edinburgh,
Scotland, UK.
Moore, Pat
SPAWAR Systems Centre San Diego,
CA, USA.
Rees, John
British Geological Survey,
Keyworth, UK.
Rothe, Mike
SPWAWAR Systems Center San Diego,
CA, USA.
Simmons, Jim
Bio Med Neuroscience, Brown University,
Providence, RI, USA.
Simmons, Rob
NAVASEA: Program Management,
Office for Explosive Ordnance Disposal,
Indian Head, MD, USA.
Trucco, Andrea
Il Departmento di Ingegneria Biofisica ed
Elettronica, University of Genova, Italy.
Waters, Dean
School of Biology,
University of Leeds, UK.
Zimmer, Walt
NATO SACLANT Undersea Research
Center, La Spezia, Italy.
Zorikov, Tengiz
Institute of Cybernetics,
Georgian Academy of Sciences,
Tbilisi, Georgia.

Appendix 3 – Presentations

3a Medical challenges and needs – *Norman McDicken*

3b Military and environmental challenges and needs – *Rob Simmons (US Navy), Bob Kennedy (US Army Corps of Engineers) and John Rees (British Geological Survey)*

3c Results of recent research on bats - *Jim Simmons*

3d Overview of dolphin bioacoustics – *Pat Moore*

3e Bat cochlear research - *Chris Clarke*

3f Signal processing applications – *Laurie Linnett*

3g Advances in transducer research –*Gordon Hayward*

3h Exploiting very short arrays –*Andrea Trucco*

3i Collaborative research efforts for the UK – *John Rees*

3j Human assistance research – *Dean Waters*

3k Biological systems – *Les Atlas with input from Jim Simmons, Dean Waters, Chris Clark and others*

3l Processing bioacoustics signals – *Ivars Kirsteins with input form Laurie Linnett, Dick Altes (submitted in absentia), Andrea Trucco, Walter Zimmer and others*

3m Bio-mimetic sonar: results achieved and the road to improvement –*Tengiz Zorikov with input from others*

3n Transducer Equalisation Techniques - *Paul Doust*

3o BAUUV - *Matt Geen*

3p Echolocation in the Egyptian fruit.bat - *Dean Waters*

3q Time/aspect varying biosonar targets - *Dick Altes*

3r Basic Science in Bioacoustics - *Group 1*

3s Information Processing – *Goup 3*

3t Application Procedures – *Group 4*

BRITISH GEOLOGICAL SURVEY RESEARCH REPORT CR/04/201

Science, Technical Innovation and Applications in Bioacoustics:Summary of a Workshop

Allen R., Anderson T., Atlas L., Clark C., DeVaud F., Doust, P.,Fay J., Geen, M., Gunn D., Hastings M., Haun J., Hayward G., Jackson P., Kennedy R.,Kirsteins I., Langhorne N., Linnett L., McDicken N., Moore P., Rees J.G., Rothe M., Simmons J., Simmons R., Waters D., Zimmer W., and Zorikov T.

Appendix 3.

Appendix 3a

Norman McDicken

Medical Challenges
&
Needs

Norman McDicken and Tom Anderson

Medical Physics

University of Edinburgh

Basic Ultrasound Physics
&
Engineering

- Similar to -
  - Non-destructive testing
  - Sonar (Radar)
  - Seismic prospecting

- Differences
  - Ultrasonic frequencies (2 to 50 MHz)
  - Propagation in soft tissue
  - Manipulation of subject
  - Competing imaging techniques

Medical Ultrasound

- 20 % of all medical imaging examinations
- Multi-billion pound industry
- Sophisticated technology
- A technology well-suited to hospitals
- Versatile (wide range of types of application)

Physics

- Narrow beams from hand-held transducer
- Array transducers
- Speed of ultrasound (1540 m/s)
- Non-linear propagation (harmonics)
- Scattering (tissue information)
- Doppler effect (blood flow)
- Micro-bubbles (contrast agents)

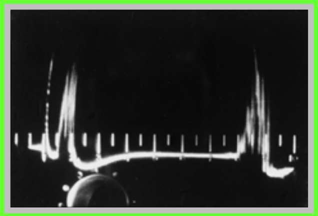
Development of Medical Ultrasound

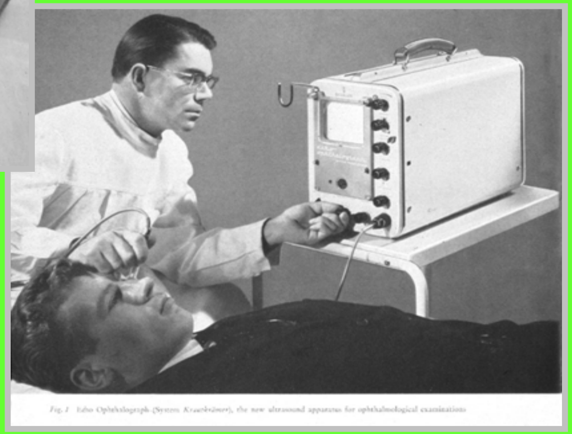
- A-scan (limited use)
- B-scan
- Real-time B Scan
- 3D Real-time B-scan
- Doppler blood flow detection
- Doppler blood flow images
- Harmonic imaging
- Coded pulse sequences
- Portable units

Origins

Ultrasound - - humble origins

- NDT flaw detector





Obstetrics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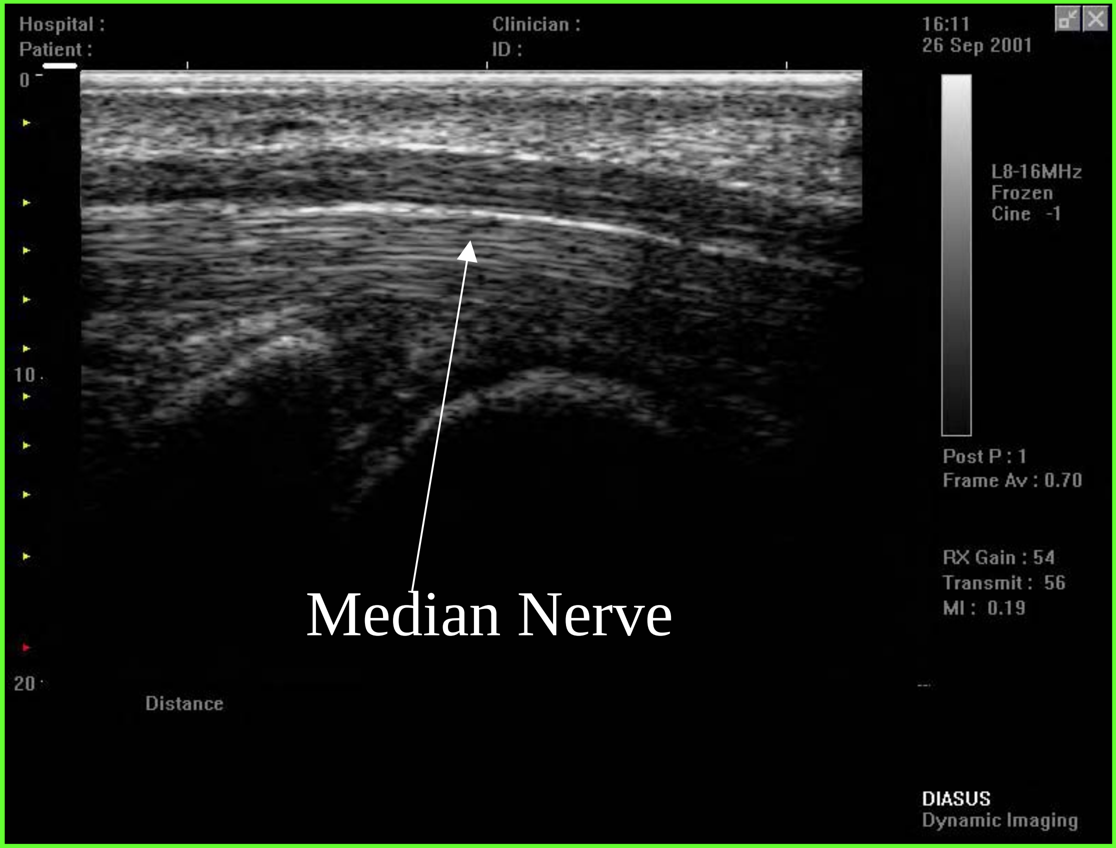
ATL
Map 3
170dB/C 3
Persist Med
2D Opt:Gen
Fr Rate:Max
XRes™
LIMB-BODY WALL COMPLEX
XRES™ TECHNOLOGY


HDI 5000
L12-5 50 OB/Gen
11:36:15 am
TIb0.1 MI 0.44
Fr #3 6.5 cm
ATL
Map 3
170dB/C 1
Persist Off
2D Opt:FSCT
Fr Rate:Surv
SonoCT™
XRes™
FETAL NECK
SonoCT™ IMAGING WITH XRES™ TECHNOLOGY

Radiology

HDI 5000
DUKE UNIVERSITY
C5-2 Abd/Gen
11:00:58 am
TIs 0.4 MI 1.3
Fr #105 16.7cm
ATL
Map 3
170dB/C 2
Persist Off
2D Opt:HSCT
Fr Rate:Targ
SonoCT
0
5
10
15
LIVER / ASCITES
HARMONIC SonoCT™ IMAGING

Musculoskeletal Imaging



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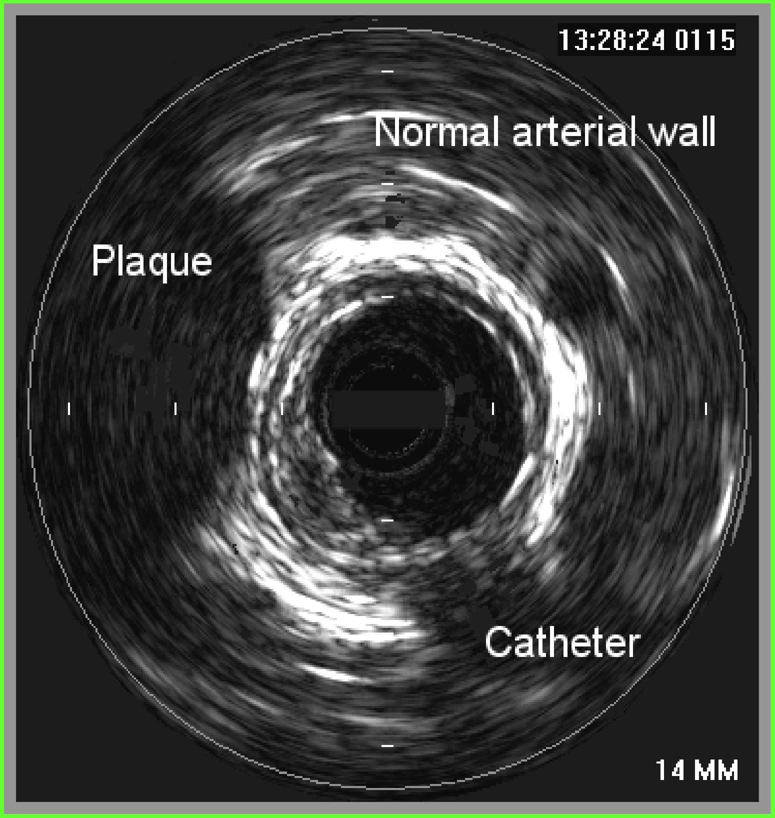
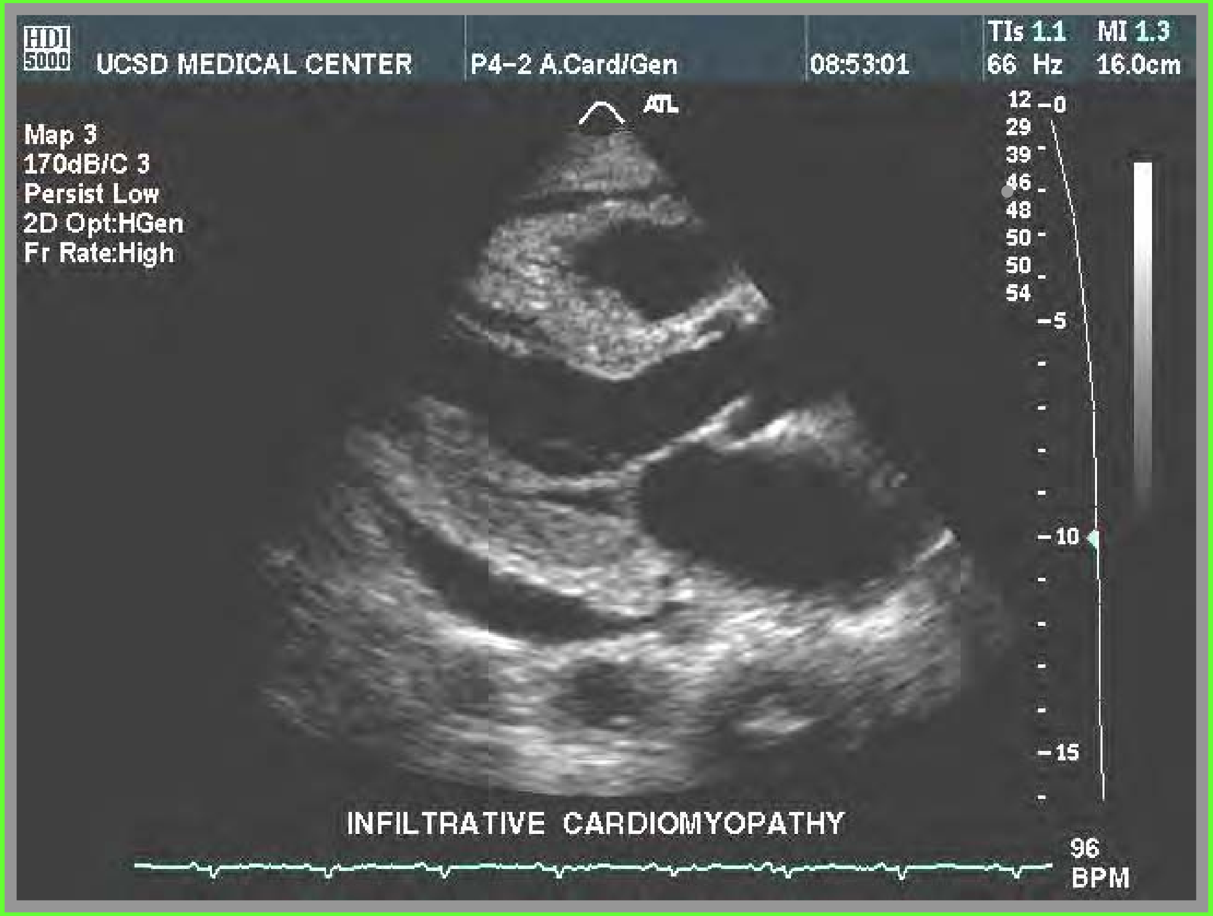


Cardiology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UCSD MEDICAL CENTER
P4-2 A.Card/Gen
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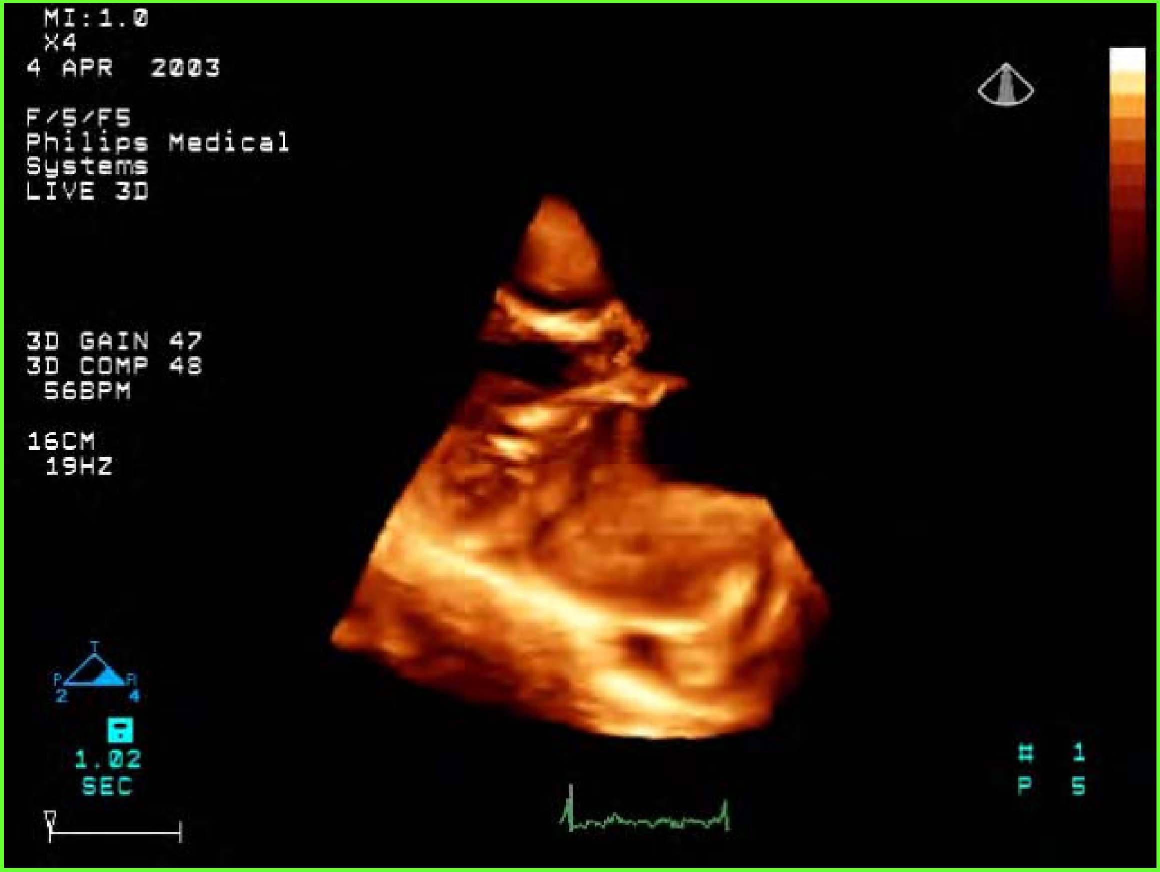
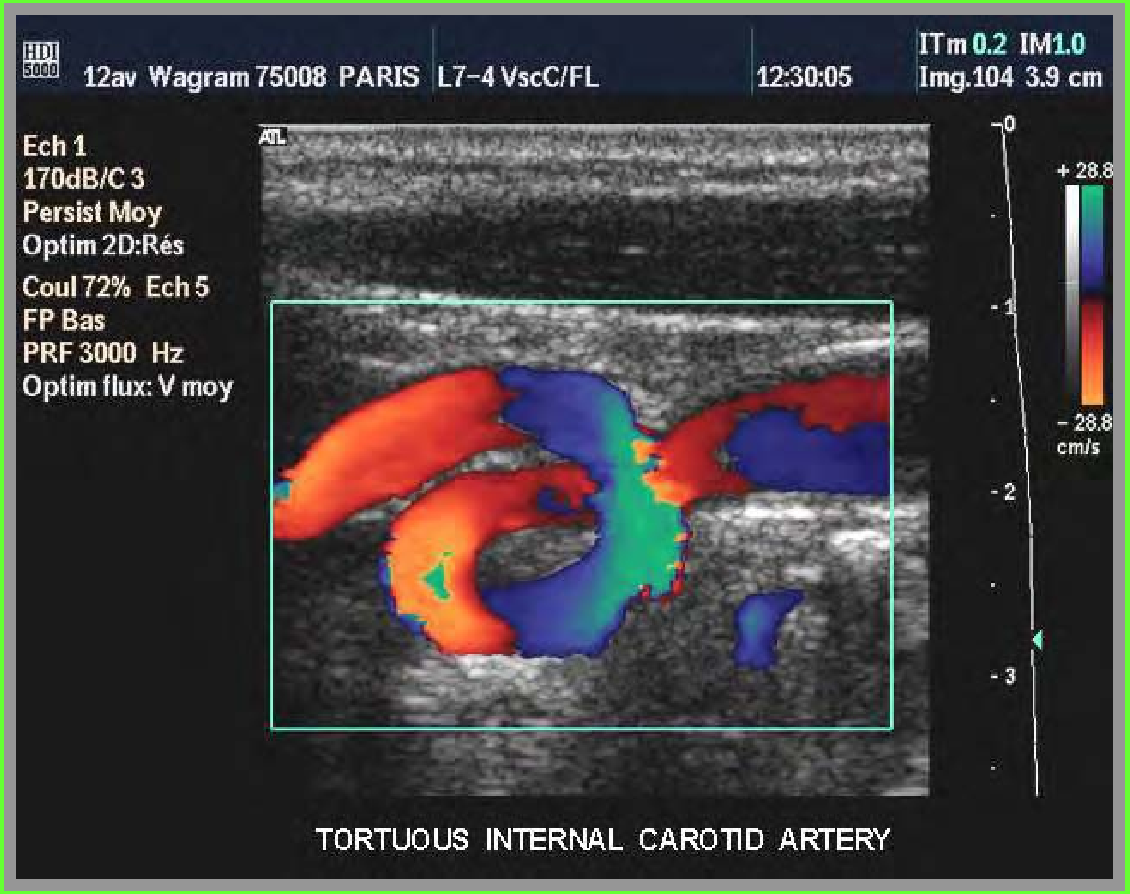
INFILTRATIVE CARDIOMYOPATHY
96
BPM

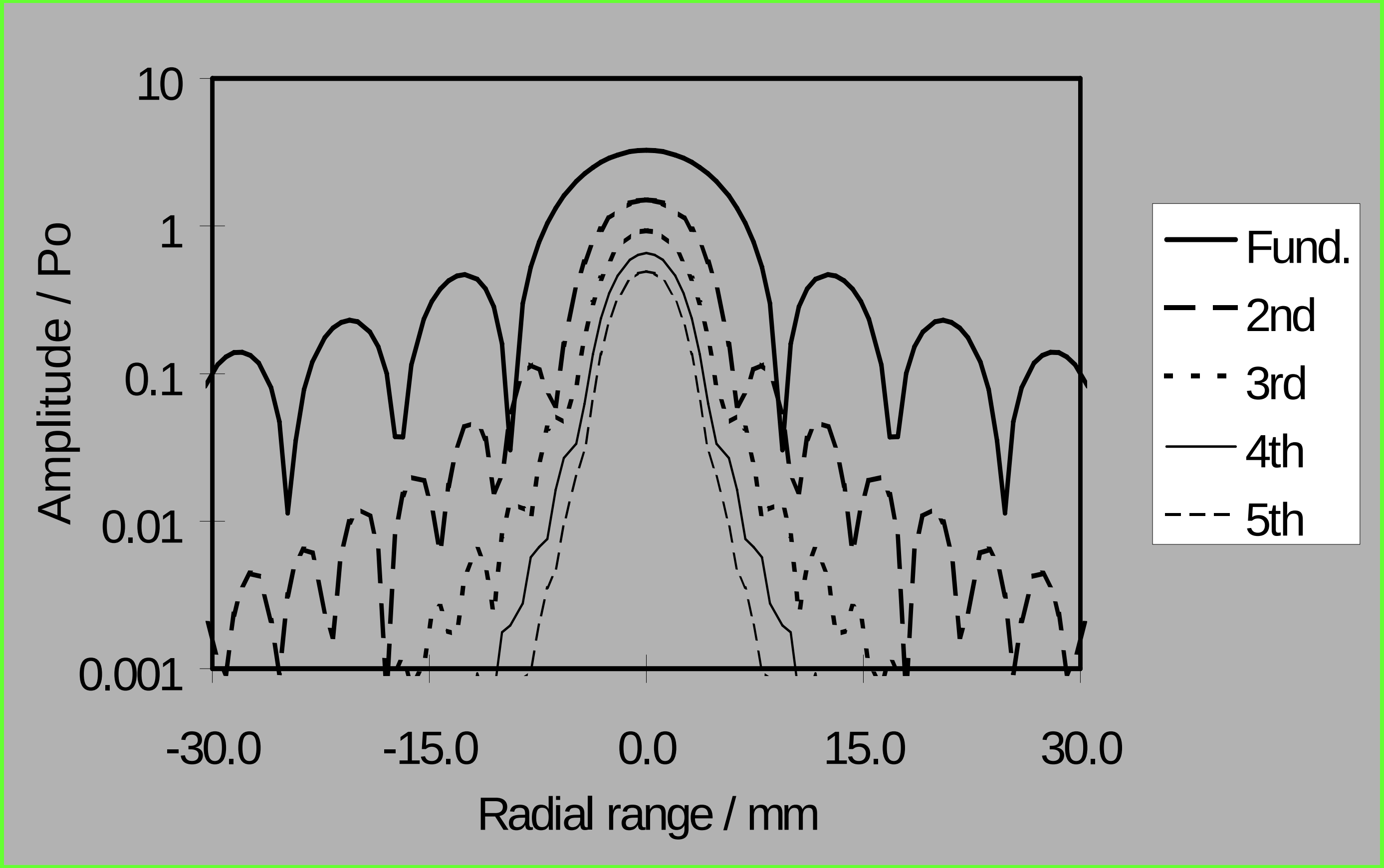
3D Cardiology



Doppler Colour Flow Imaging

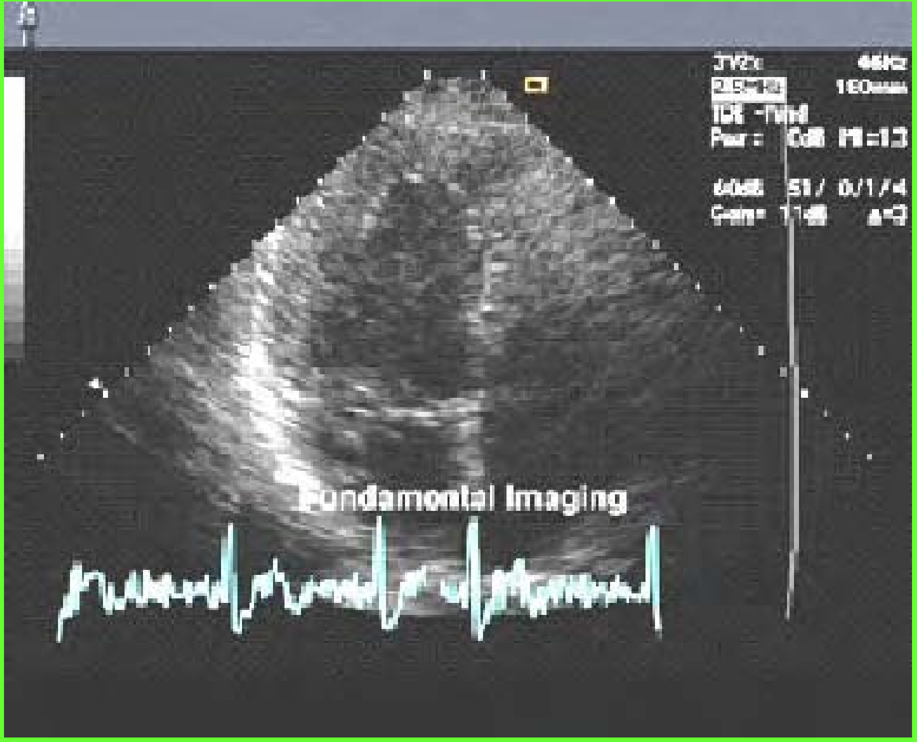


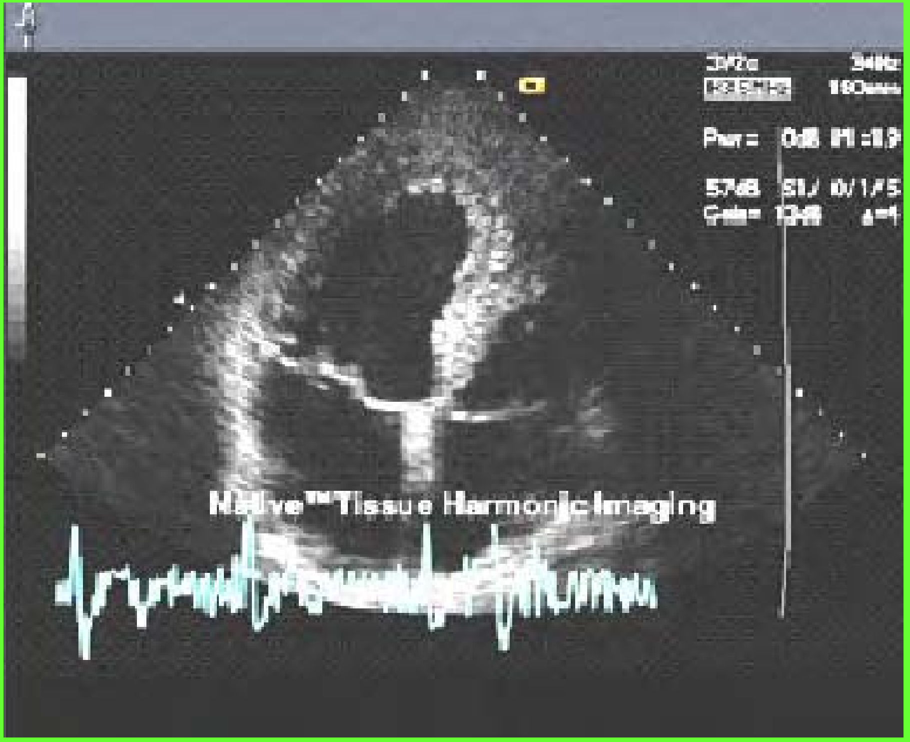
Harmonic profiles



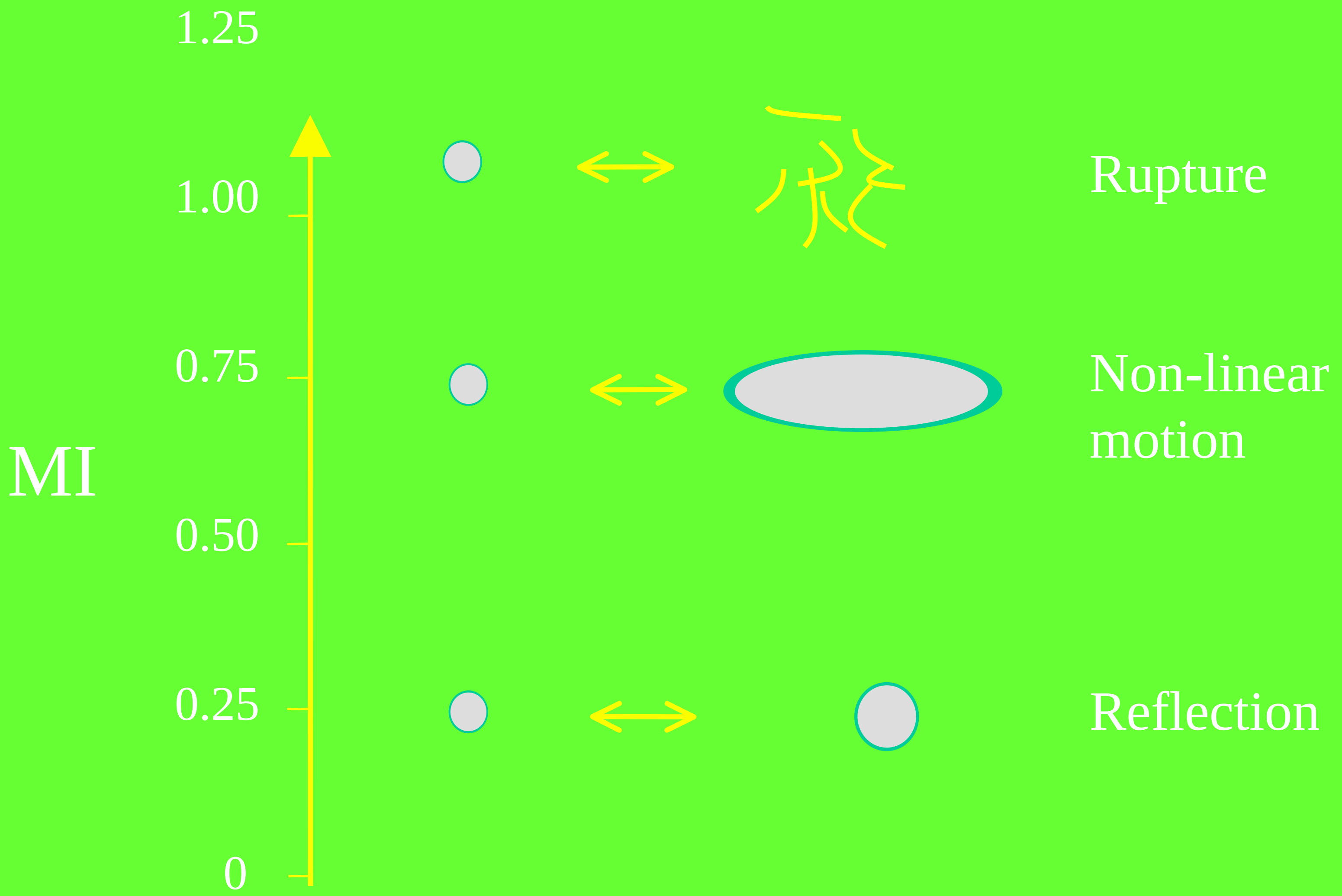
Curtesy - F. A. Duck

Non-linear propagation

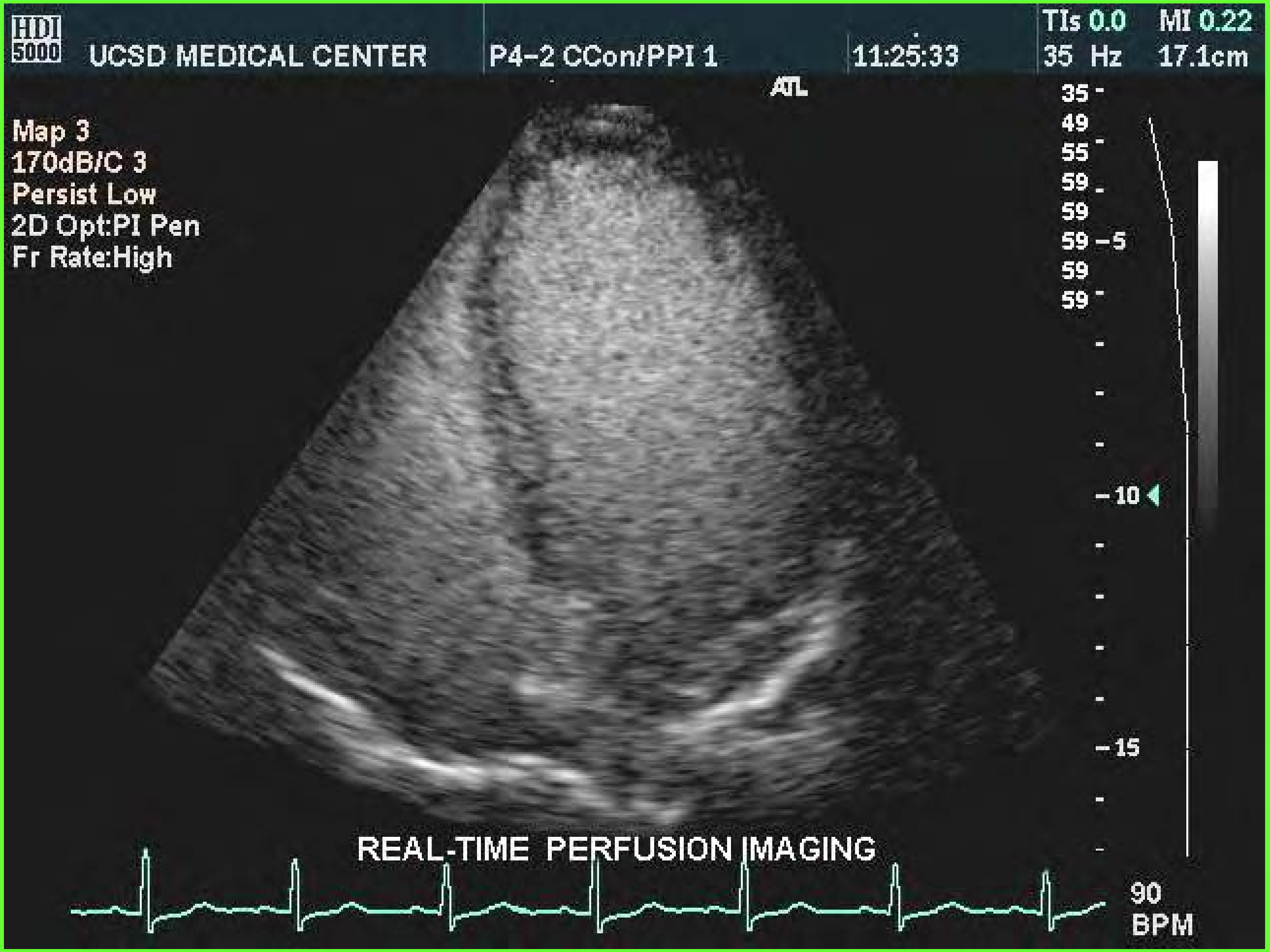




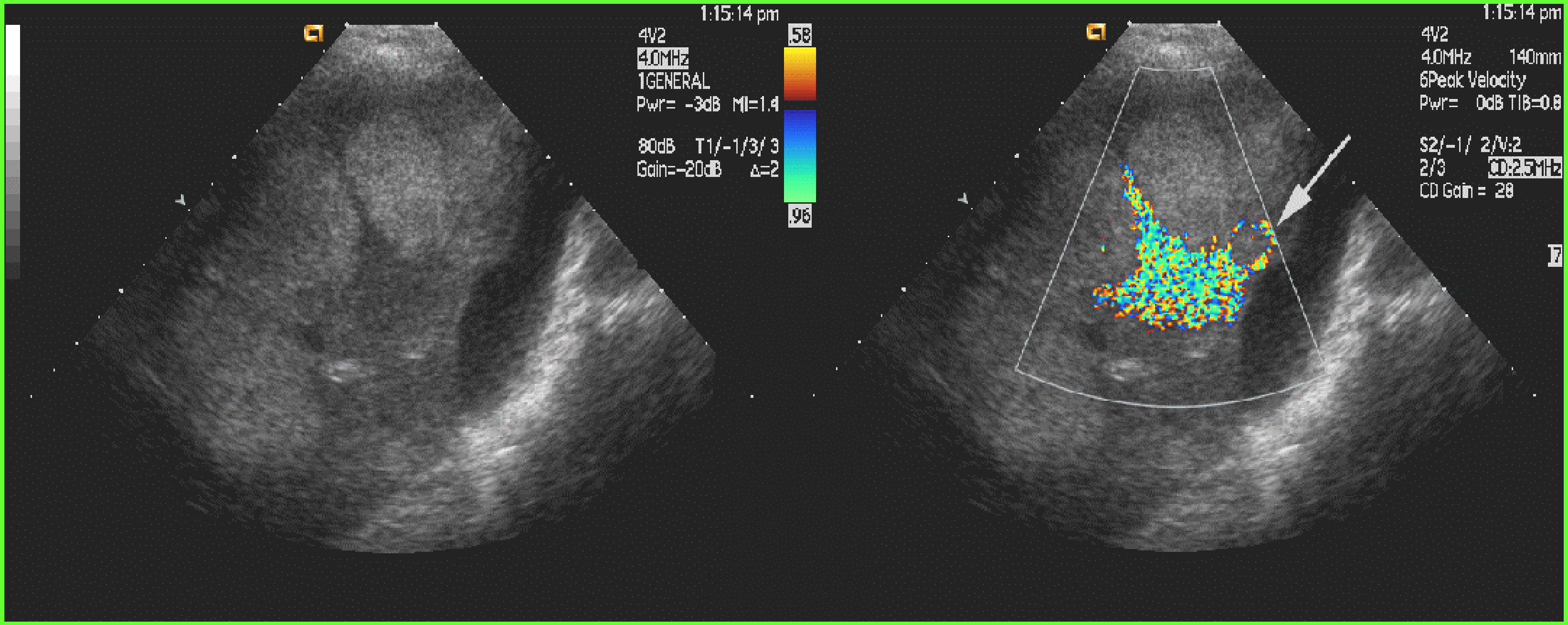
Behaviour with incident pressure



Contrast - Cardiology

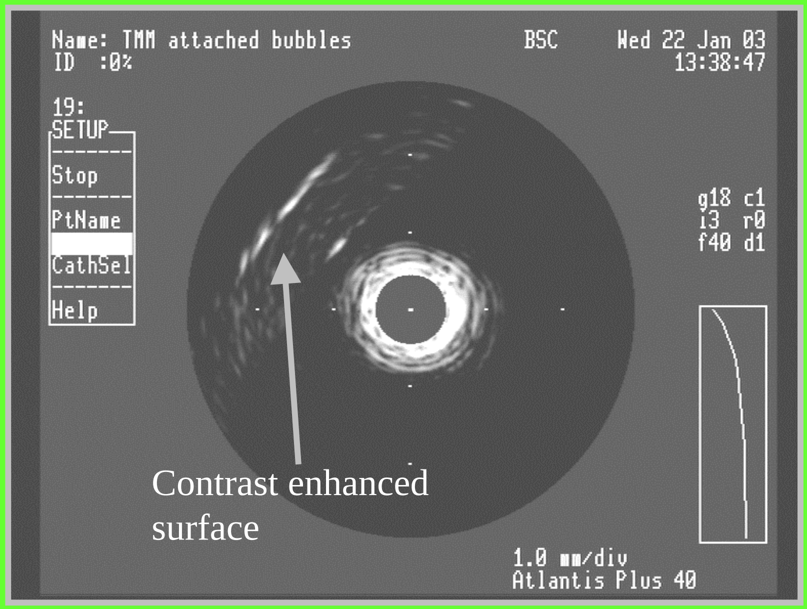


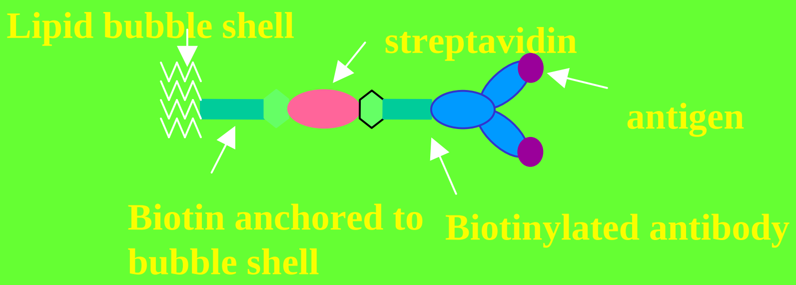
Schering- ruptured bubbles



Curtesy M.
Blomly

Targeted Contrast Agents





Small animal imaging

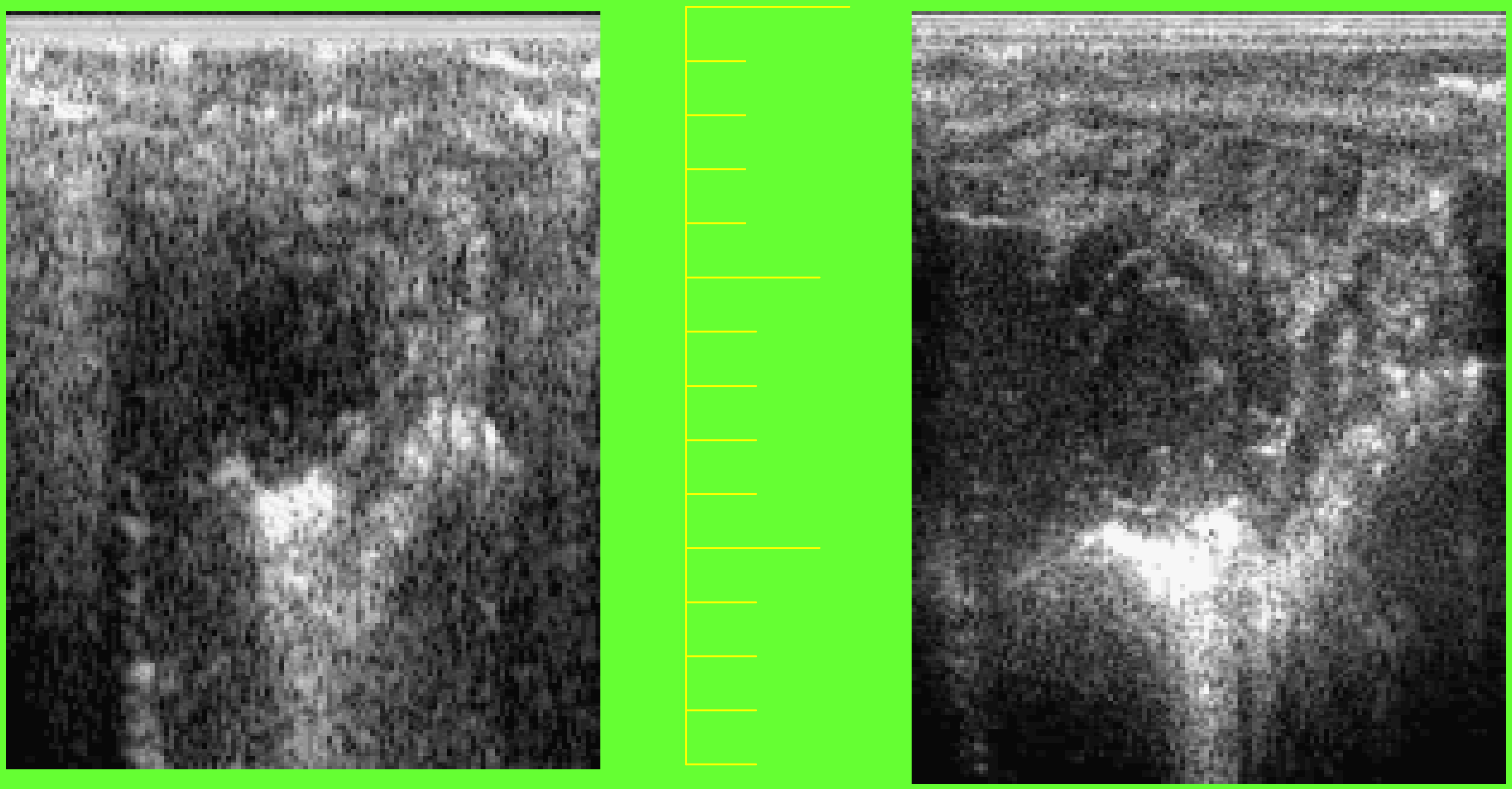
Cardiac Imaging in Mice

The Challenge

Mouse heart

- 7mm diameter
- 8 beats/sec

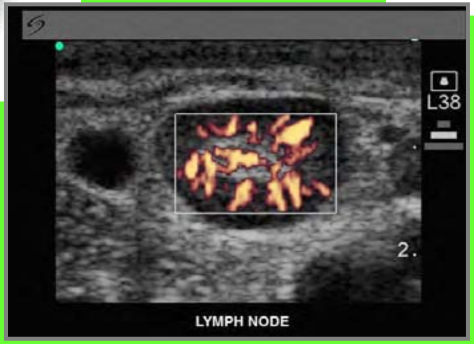
Mouse Heart



L5-10MHz L16-28MHz

Laptop scanners – the future?

Hand-carried ultrasound system



Attractions

- Non-invasive
- Safe (patient and operator, repeat scans)
- Soft tissue detail
- Versatile
- Portable
- Low cost (capital and running)
- Active contrast agents
- (Weaknesses – see Needs)

Challenges and Needs 1

- Tissue characterisation (needle biopsy)
- Image through bone
- Quantitative perfusion with contrast agents
- Targeted contrast agents
- Real-time 3D imaging
- True 3D blood flow imaging

Challenges and Needs 2

- Improved resolution (spatial, contrast)
- Reduction in number of poor images (beam distortion)
- User-friendly machine
- Reduced operator dependence of results (smart machines?)
- Wider bandwidth transducers
- Higher frequency transducers
- Improved knowledge of tissue properties

The Future

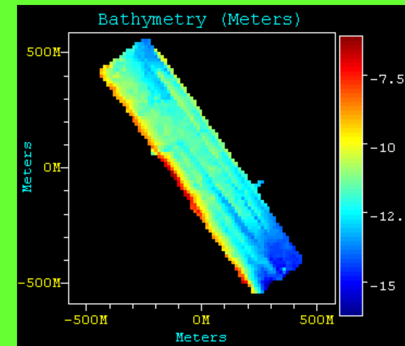
One source to try

Or lets listen to Nature

Investment highly recommended

Appendix 3b

Rob Simmons



Military and Environmental Challenges and Needs

Rob Simmons
PEO LMW (PMS-EOD)
Program Manager for Small UUV Programs

Outline

- Basic UUV system requirements
- Small UUVs in tactical MCM Operations
- The “Next Step(s)” in the evolution of small UUV’s
- Challenges for the future: Notional Role of Bioacoustics for Small UUV’s
- Conclusions

Basic UUV Requirements

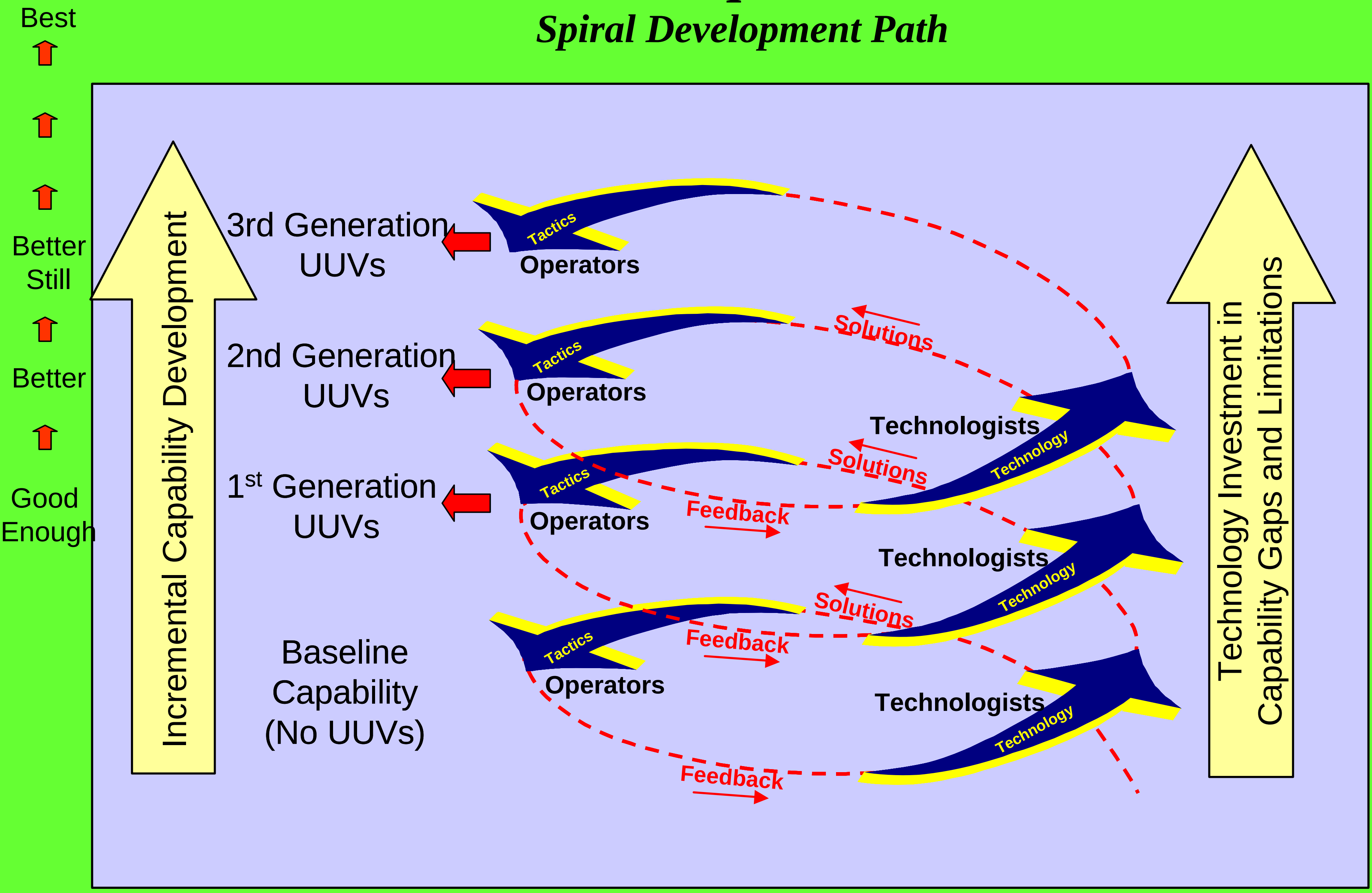
- COMLANTFLT endorsement to a COMEODGRU TWO letter outlining requirements for small UUVs for Navy EOD underwater UXO operations.
  - ***"UUVs will allow divers to focus*** ***on the more complex and arduous task of neutralization, in place render safe operations and exploitation intelligence gathering."***

    Paul Ryan
    RDML, USN
    CLF N8
- Post 9-11 REMUS Employment in Carrier Basin/San Diego.
  - ***"Search and reacquisition of targets consumes an inordinate amount of available mission time using current technologies. UUV employment will act as a force multiplier and allow EOD technicians and divers to use their limited bottom time rendering safe underwater ordnance or conducting salvage operations vice conducting extensive search operations."***

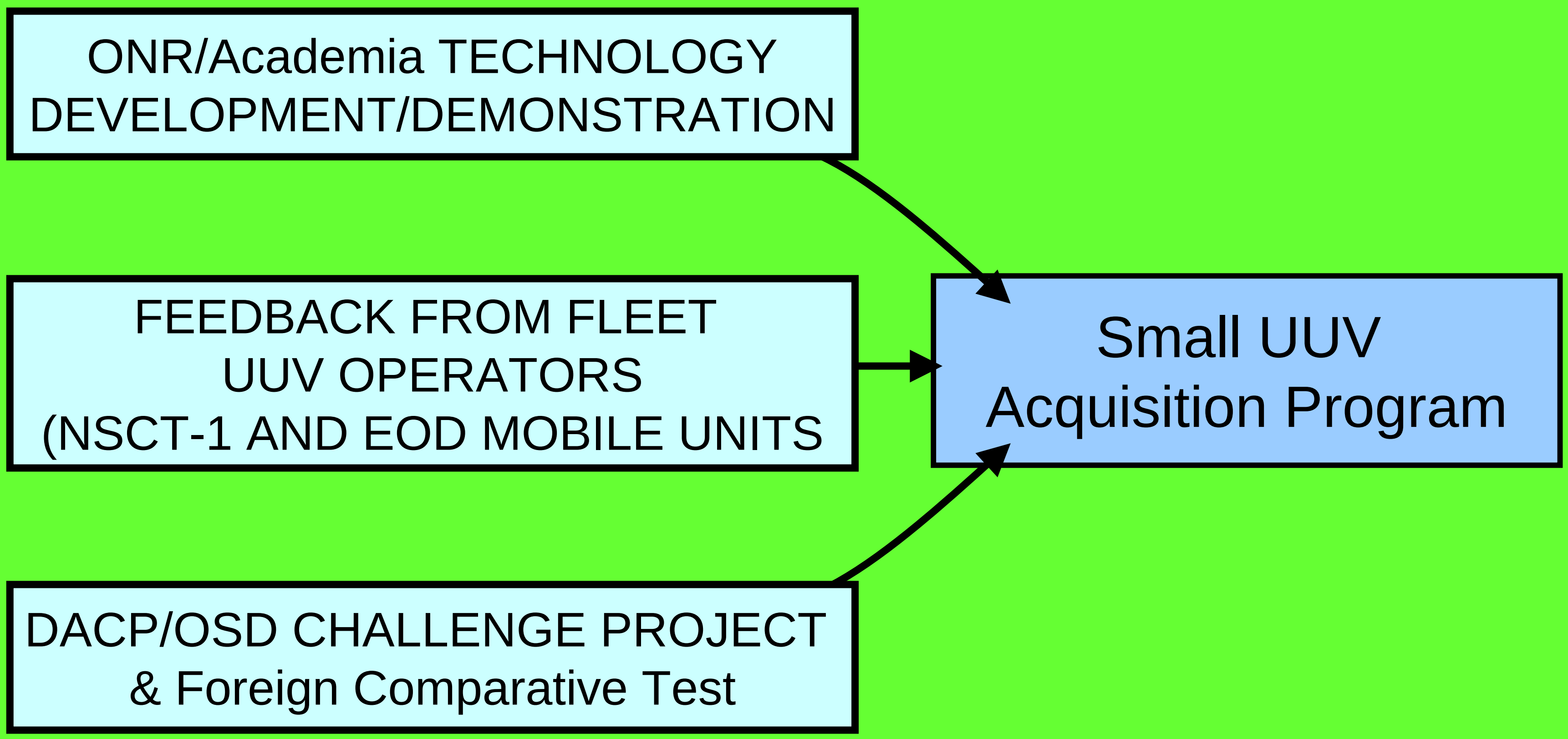
    W. E. Wright,
    CAPT, USN
    COMEODGRU ONE

Acquisition Strategy for meeting the Basic Requirements

Spiral Development Path

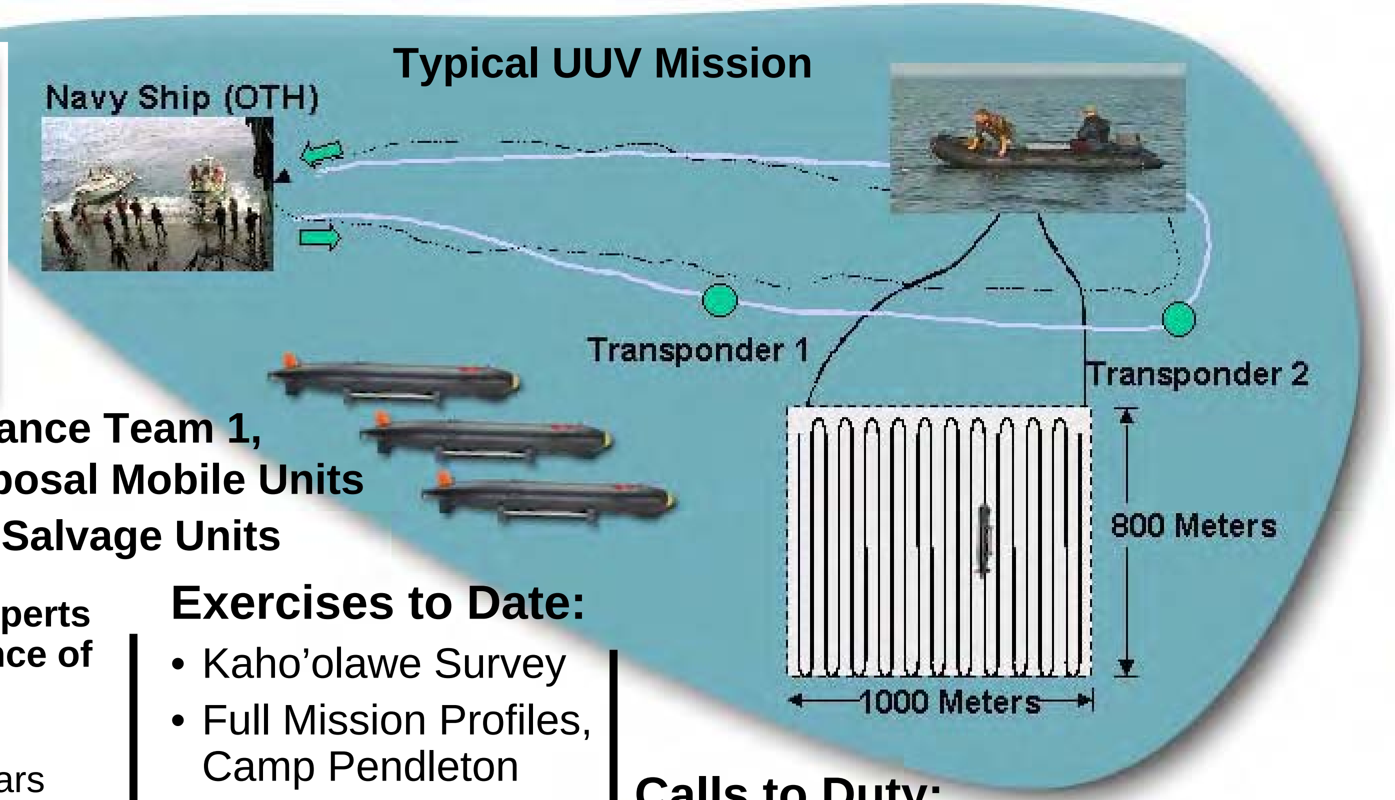


Technology to Capability Transition for Basic UUV Requirements



Small UUV’s in Tactical MCM Operations

Systems for Exploration and Reconnaissance



Naval Special Clearance Team 1,
Explosive Ordnance Disposal Mobile Units
& Mobile Diving and Salvage Units

- Maintains a cadre of Fleet **experts in operation and maintenance of small UUVs.**
- Operational Prototypes maintained/operated for 2 years
- Completed over **300 UUV “missions” to date**
- Develops SOPs and tactics for integration with MCM forces
- Provide feedback to acquisition program management and technology teams

Exercises to Date:

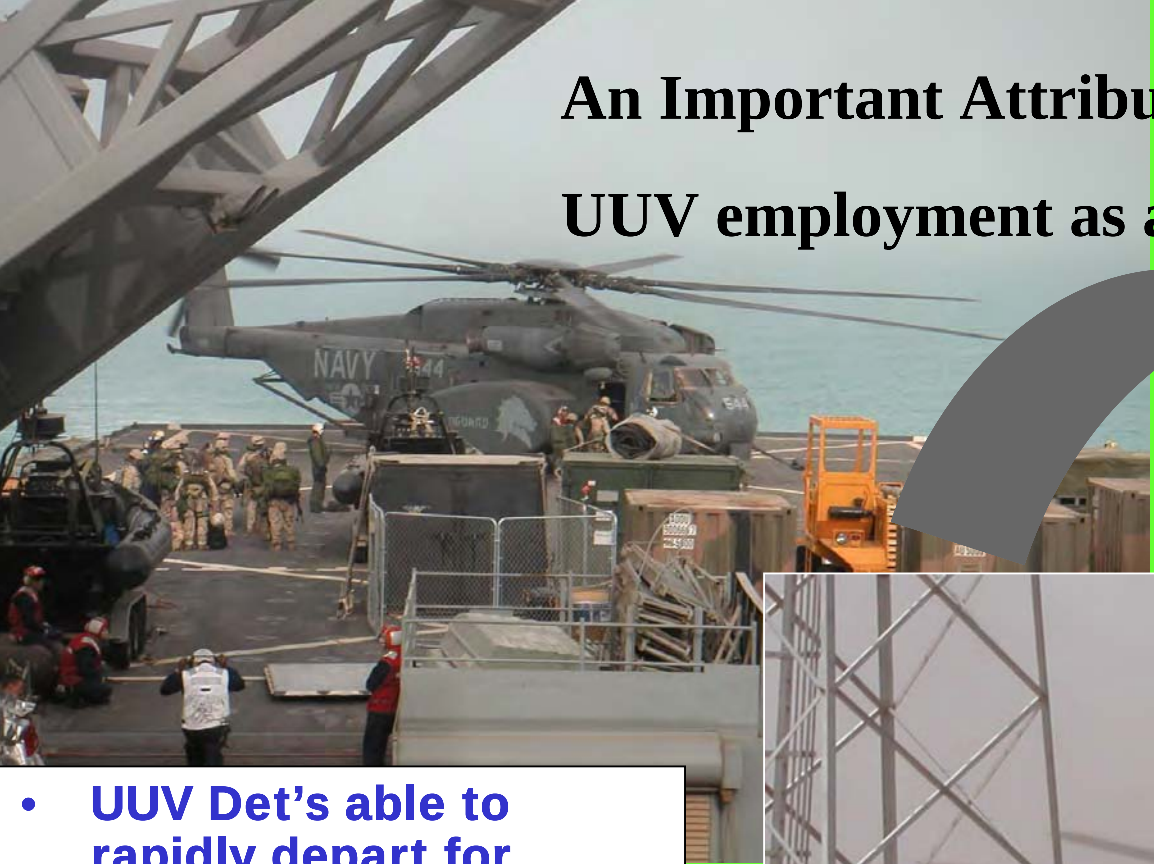
- Kaho’olawe Survey
- Full Mission Profiles, Camp Pendleton
- Exercise Bank Shot, North Carolina
- RIMPAC-02, Hawaii
- FBE-J, Camp Pendleton

Calls to Duty:

- San Diego Bay Carrier Pier Search (Post-9/11)
- Deployed to C5F for ATFP Operational Demonstration – ASU BAHR
- **Umm Qasr, IRAQI FREEDOM**

An Important Attribute:

UUV employment as a “Suitcase System”



- **UUV Det’s able to rapidly depart for forward operation via rapid airlift**
- **Multiple UUVs per system**
- **Men, equipment, and a week’s worth of food and water need to take limited airlift**
- **Rapid UUV employment after equipment arrival**

Typical U.S. Navy UUV Operators
Knowledge, Skills, & Abilities
18 month Rotation

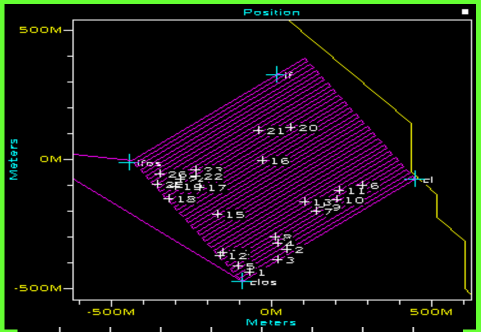
- Are High School Graduates
- Possess basic computer skills
- Have basic troubleshooting experience
- Can operate basic hand tools
- Understand/apply general tool safety
- Can use a multi-meter and can perform battery charging steps
- Have experience operating portable GPS sets.
- Are qualified/can perform basic first aid.
- Possess knowledge/ability to do general record keeping
- Possess basic line handling skills
- Can read nautical charts
- Are normally a second class petty officer (I.e. E-5) or higher
- Have completed/graduated from an A-school
- Possess a technical rating
  - Fire control, sonar or electronics technician,Mineman

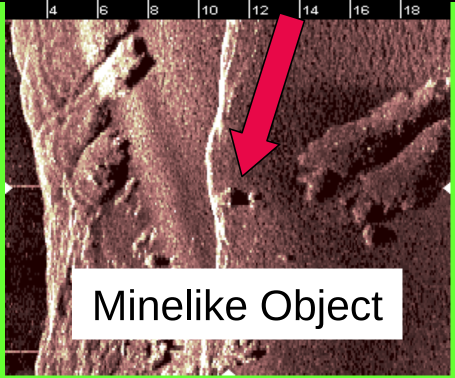
•**Exportable, modular training program is required;**

•**Computer-aided training allowing for simulator-type capabilities**

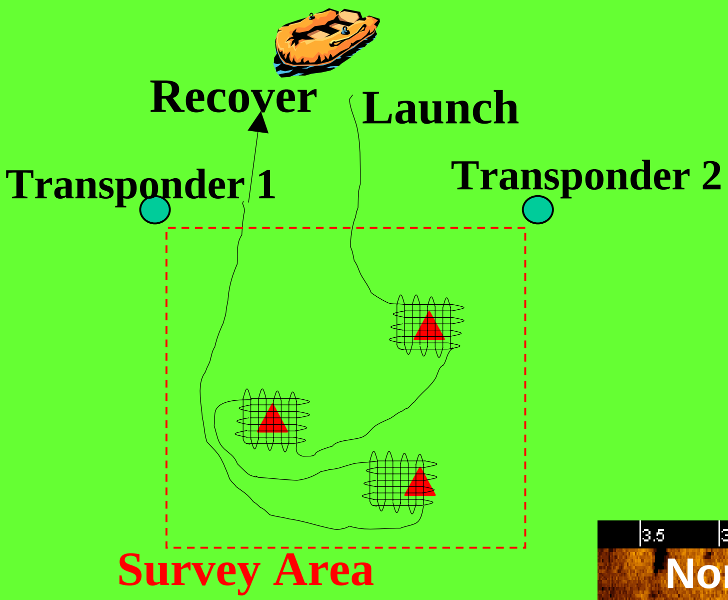
First Generation of Small UUVs
Exploiting the benefits of Mature HF-SLS and CCD Sensors
Search-Classify-Map-Reacquire-ID

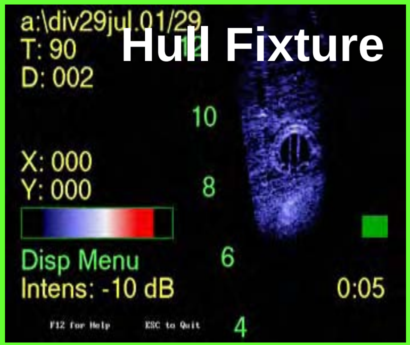
Search-Classify-Map

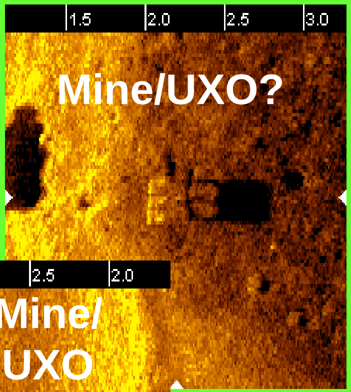




Reacquire-ID







__Second__ ***Generation of Small UUVs***
Addressing Near-Term High Priority Missions
Rapid Response Ship Hull Search and Object Localization

__RESPONSE TIME IS THE ISSUE__

- **Assemble a search team.**
- **Tag out intakes, screws, sonars, etc.**
- **Coordination with other ships.**
- **Conduct hull search**

__COMMON DIVER CHALLENGES__:

- **Poor visibility**
- **Disorientation**
- **Tending line entanglement**
- **Hazardous conditions**
- **Confined spaces**

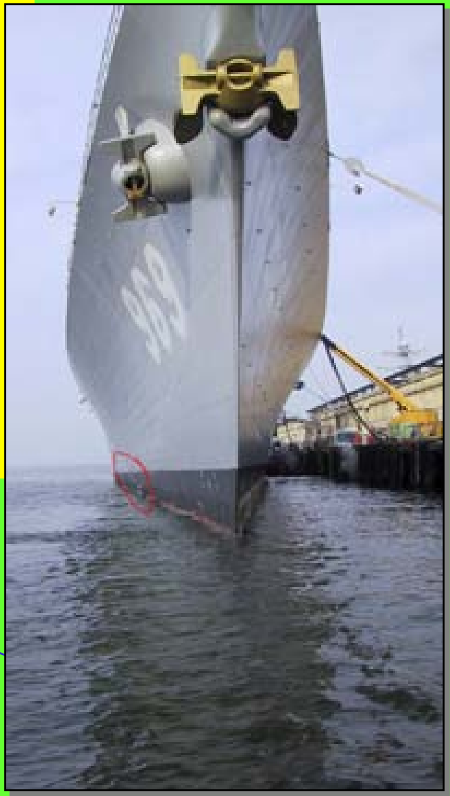
Notional Conops for 2nd Generation UUV

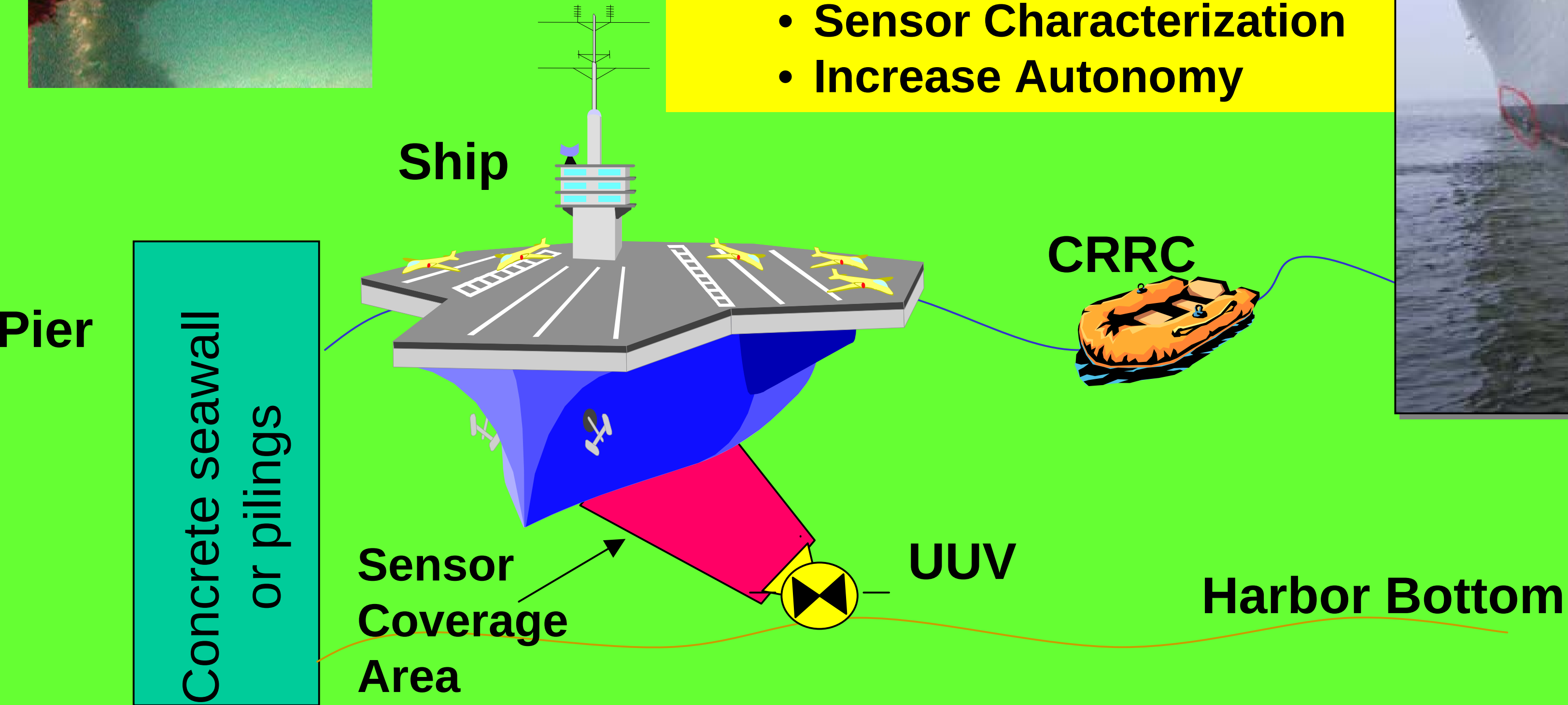
Tactical Integration & Employment of UUVs, Divers and Other Assets

Technology is **NOT YET** sufficiently advanced for UUVs to search effectively in under-hull/pierside operations,

<u>but S&T efforts are ongoing:</u>

- **Precise Navigation**
- **Sensor Characterization**
- **Increase Autonomy**





3rd Generation UUVs

Chemical Sensing in a Marine Environment (CSME) with Adaptive Mission Planning (AMP)

Explosives Sensor Development

- **Explosives Detection Using Amplifying Fluorescent Polymers**
  - Nomadics, Inc.; Colin Cummings
- **Explosives Detection in Seawater on a Microchip**
  - Collins, NRL & Wang, NM State Univ.)

UUV Application

- **Develop more efficient/effective (smarter) UUVs by integrating an explosive sensor with:**
  - AMP technology;
  - High Fidelity UUV sensors
- **Provide effective search/object, detection, localization and identification.**

FY03 Efforts

Nov 2002 - SCI Field Test

- **Test technologies with UUV in near-field area.**
  - 7/8 Successful AMP Missions.
  - REMUS UUV + TNT Sensor integration.

April '03: SCI Field Test

- **Test/evaluate source plume algorithms.**
- **Continue TNT sensor integration and test different sensors.**

June '03: 'Tests at Duck, NC.

- **Test UUV plume tracing in far-field area.**
- **Evaluate different TNT sensors on UUV:**
  - Nomadics, NMSU, Sub Chemical Systems

3rd Generation UUVs

Focus on Clutter Reduction, Enhanced Object Detect/ID

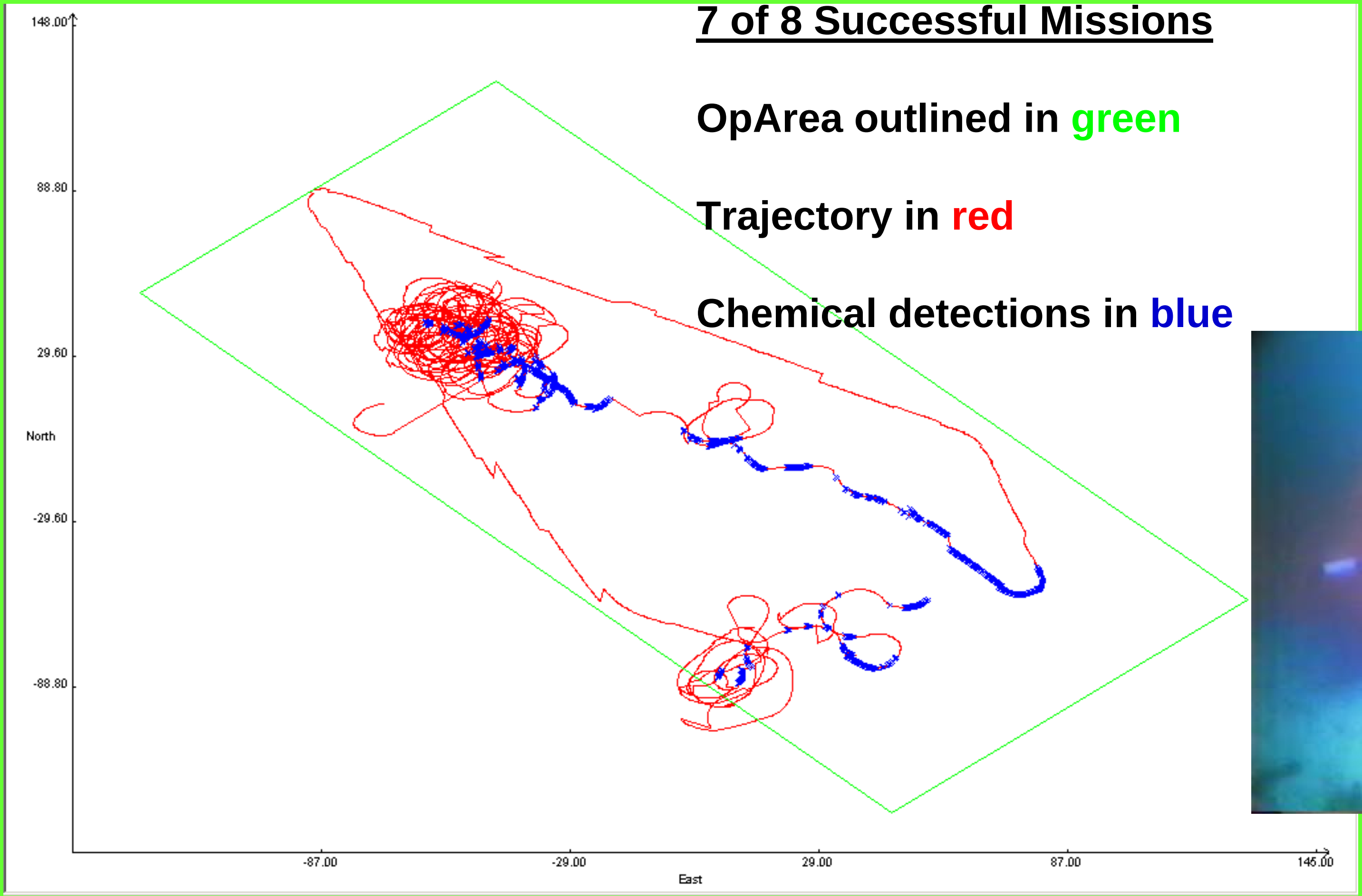
Adaptive Mission Planning/Plume Tracking

7 of 8 Successful Missions

OpArea outlined in green

Trajectory in red

Chemical detections in blue



Some Day – “*Mowing the Lawn*” may no longer be the best way!

Challenges for the Future
(A Notional Role of Bioacoustics)

Technical Challenges

- Clutter reduction, enhance object detection and ID.
- Buried object classification
- Baseline-free navigation solutions
- Up-looking (under hull) sensing, maneuver and navigation
- Advanced underwater communications

ADDRESSED THROUGH ONR'S/Academia TECHNOLOGY PROGRAMS

ADDRESSED THROUGH EARLY/CONTINUOUS FLEET ENGAGEMENT

Programmatic Challenges

- Enhancing user friendly interfaces
- Capitalizing on data already collected
- Managing Post Mission Analysis Data & timeline
- Sustaining Fleet proficiency
- Mainstreaming UUVs into Fleet operations & exercises
  - **Migrate Experimental TT&P to SOPs and Doctrine**
  - **Life cycle support**

Conclusions

- UUVs are increasingly important assets in real world operations.
- Small UUVs are NOT a panacea for full-spectrum operations in all environments – but they are **already reducing operational risk** and improving effectiveness:
  - Relieving humans of mundane, expensive and dangerous underwater tasks.
  - Better informing humans on underwater tasks that they still must perform.
  - Making arduous tasks easier.
- Technologists and Academia in concert with UUV industry partners are working the transition of new capabilities to the Fleet.
- A broader range of potential future UUV operators is evolving:
  - Naval coastal warfare
  - Mobile Security Forces
  - Marine Safety & Security Teams
  - The Private Sector

KEY UUV ATTRIBUTES
Rapidly deployable
Small footprint
Affordable

Appendix 3b

Bob Kennedy

Military and Environmental Challenges and Needs: An Army Perspective

R. H. Kennedy

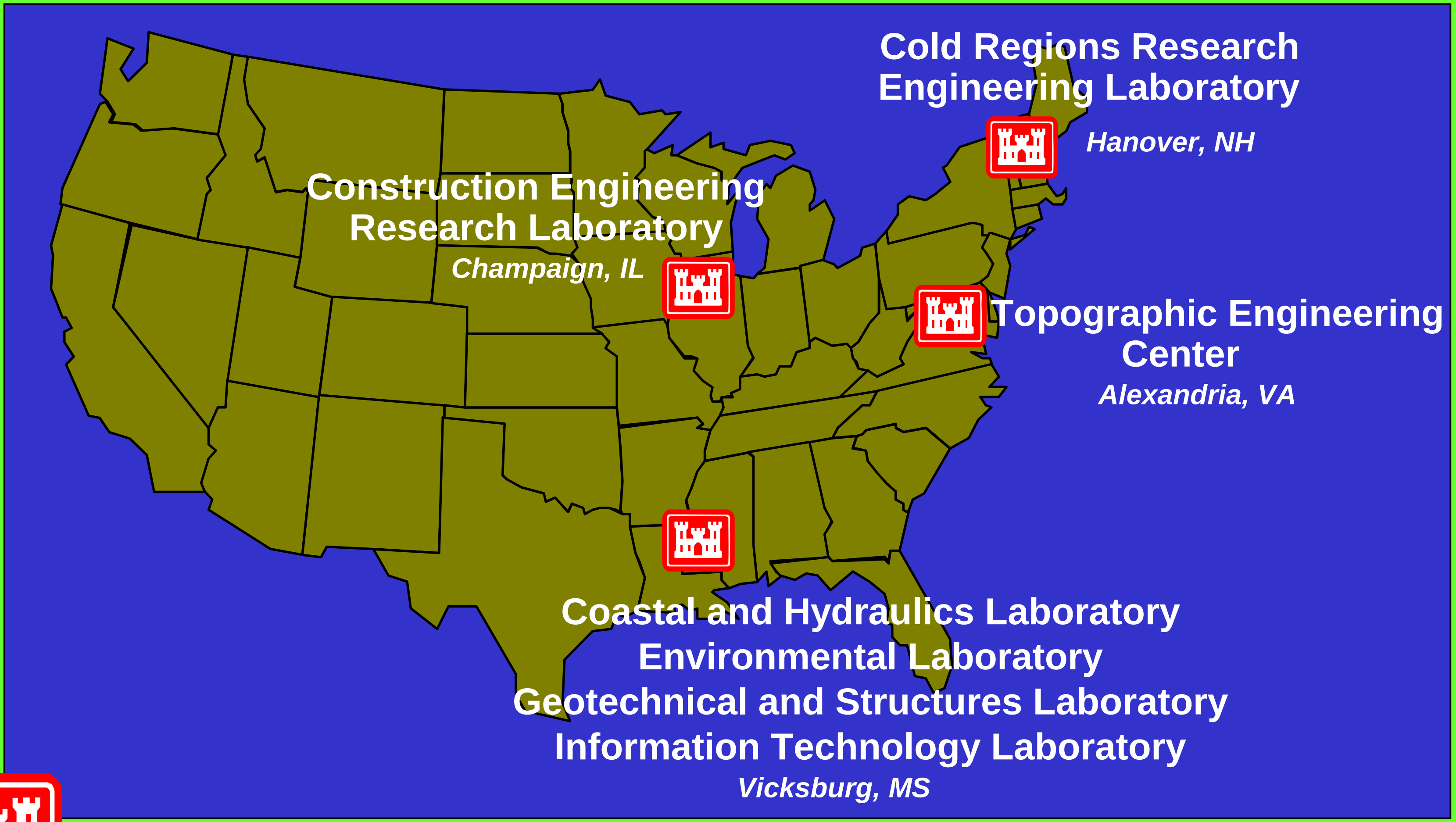
European Research Office
Engineer Research and Development Center
US Army Corps of Engineers

U. S. Army Corps of Engineers

Mission

- Provide engineering and environmental services to the nation.
- Plan, design, build and operate water resources and other civil works projects.
- Design and manage the construction of military facilities
- Design and construction management support for other defense and federal agencies.

Engineer Research and Development Center

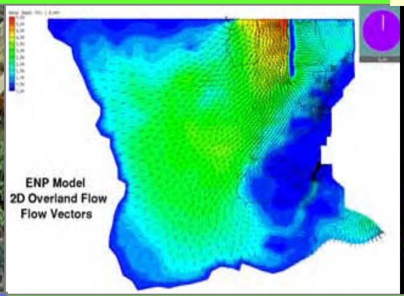


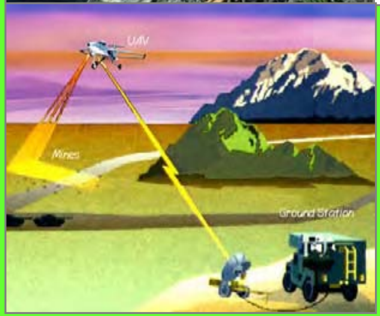
US Army Corps
of Engineers

European Research Office

Engineer Research and Development Center

Business Areas





- Environmental Quality & Installations
- Civil Works
- Military Engineering
- Battlespace Environment

Challenges and Needs

- **Unexploded ordnance (UXO)**

Challenges and Needs

- **Unexploded ordnance (UXO)**


Toussaint River andHarbor will be dredged to accomodate large vessels.

Live ordnance halts new dredging project

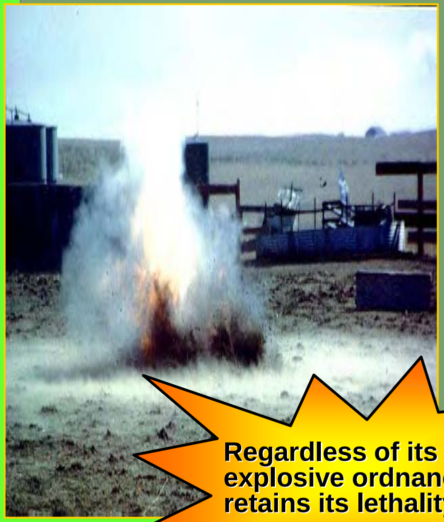
by Juliana Gardner

Former Erie Army Depot

Unexploded Ordnance

Challenge: **Enhance safety <u>and</u> significantly reduce subsurface UXO site cleanup costs, time, and efforts spent on excavating non-hazardous items**

- **Current methods result in high false target rates.**
- **Greater than $35 Billion potential liability (DoD 2003 Report to Congress).**



Regardless of its age, explosive ordnance retains its lethality

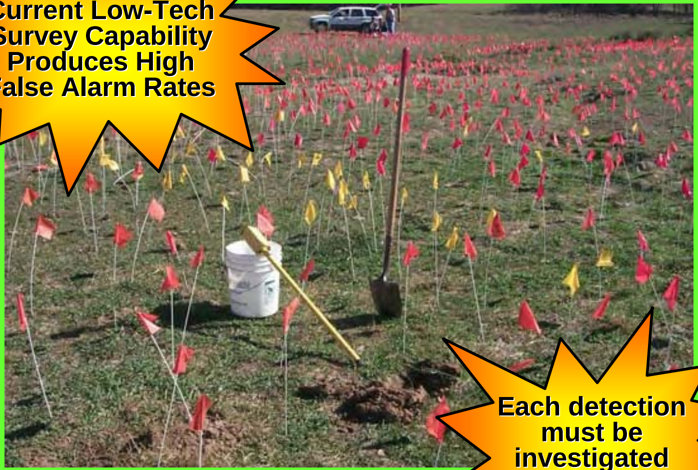
US Army Corps of Engineers

European Research Office

Unexploded Ordnance

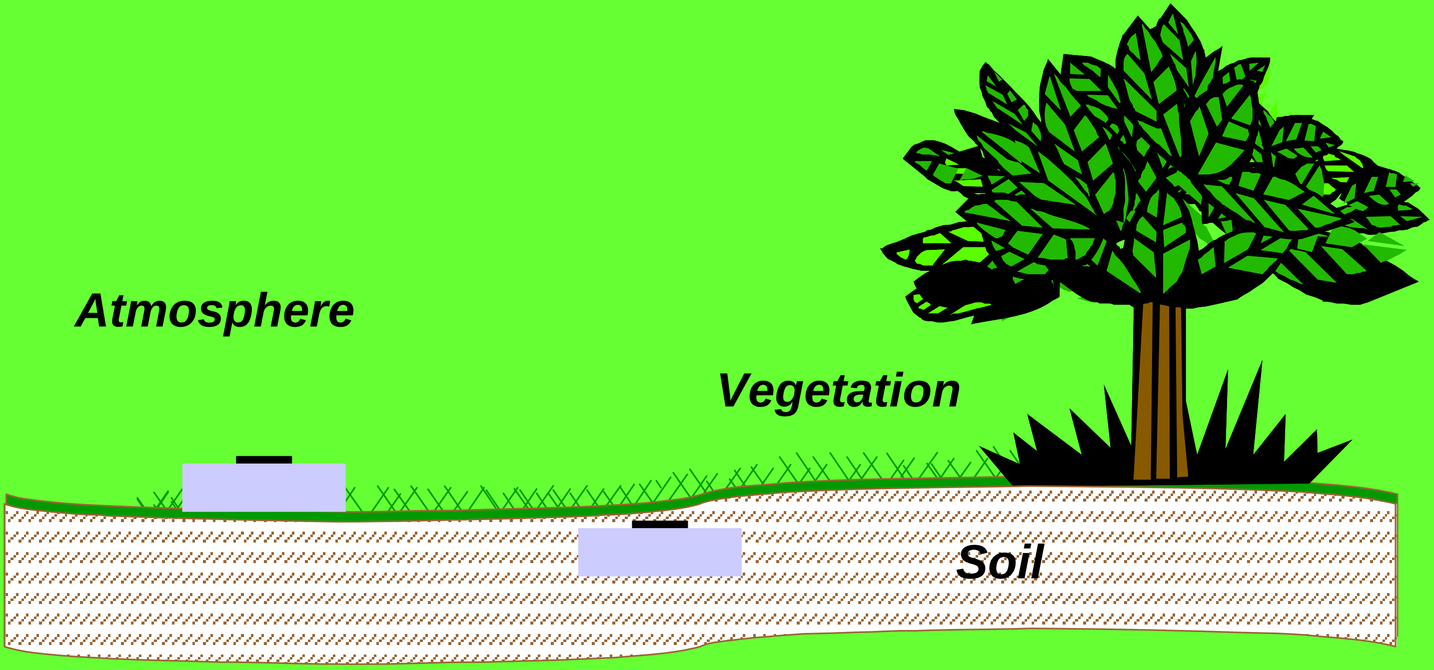
***Challenge:* Enhance safety <u>and</u> significantly reduce subsurface UXO site cleanup costs, time, and efforts spent on excavating non-hazardous items**

- **Current capability: Pd ~70 to 90%; False Alarm Rejection ~10%.**
- **Objective: Pd ~98%; False Alarm Rejection Rate ~90%**



Challenges and Needs

- Unexploded ordnance (UXO)
- **Countermine phenomenology**



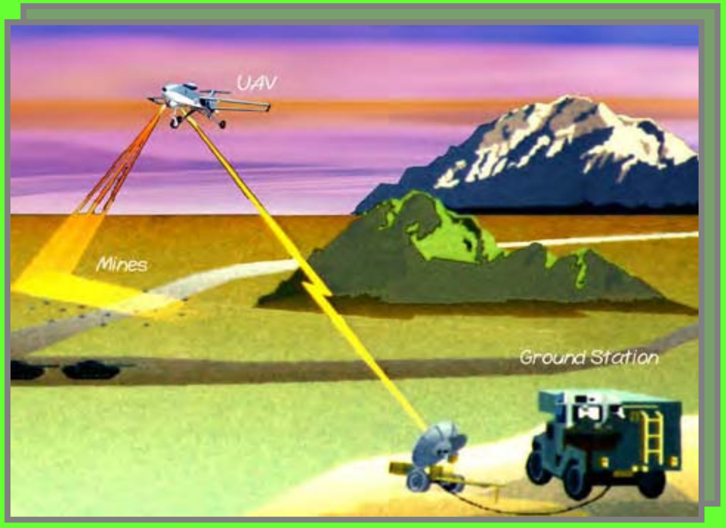
US Army Corps
of Engineers

European Research Office

Countermine Phenomenology

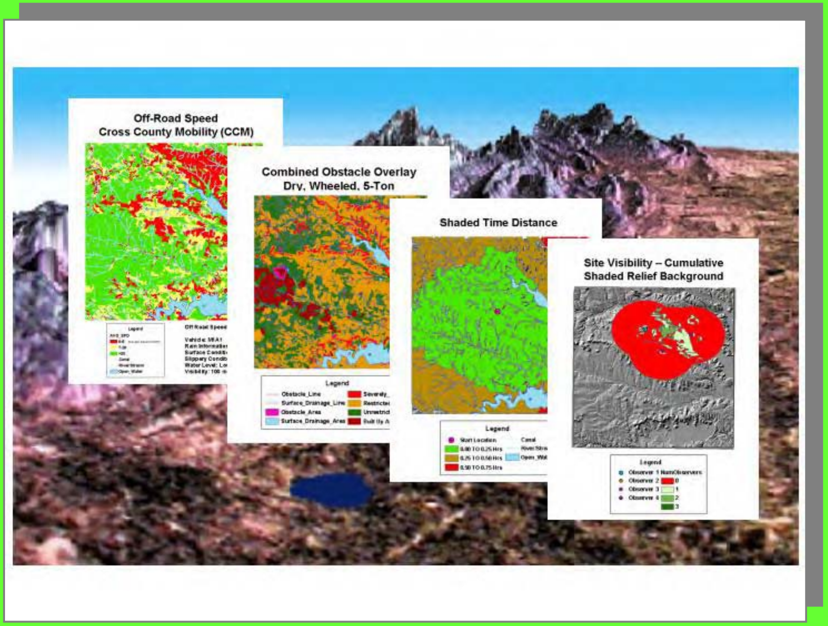
***Challenge:* Provide an understanding of geo-environmental phenomenology to predict and improve the performance of airborne and vehicular CM systems across all operational environments**

- **Improved capability to detect surface and buried AP and AT mines and minefields across all operational environments**



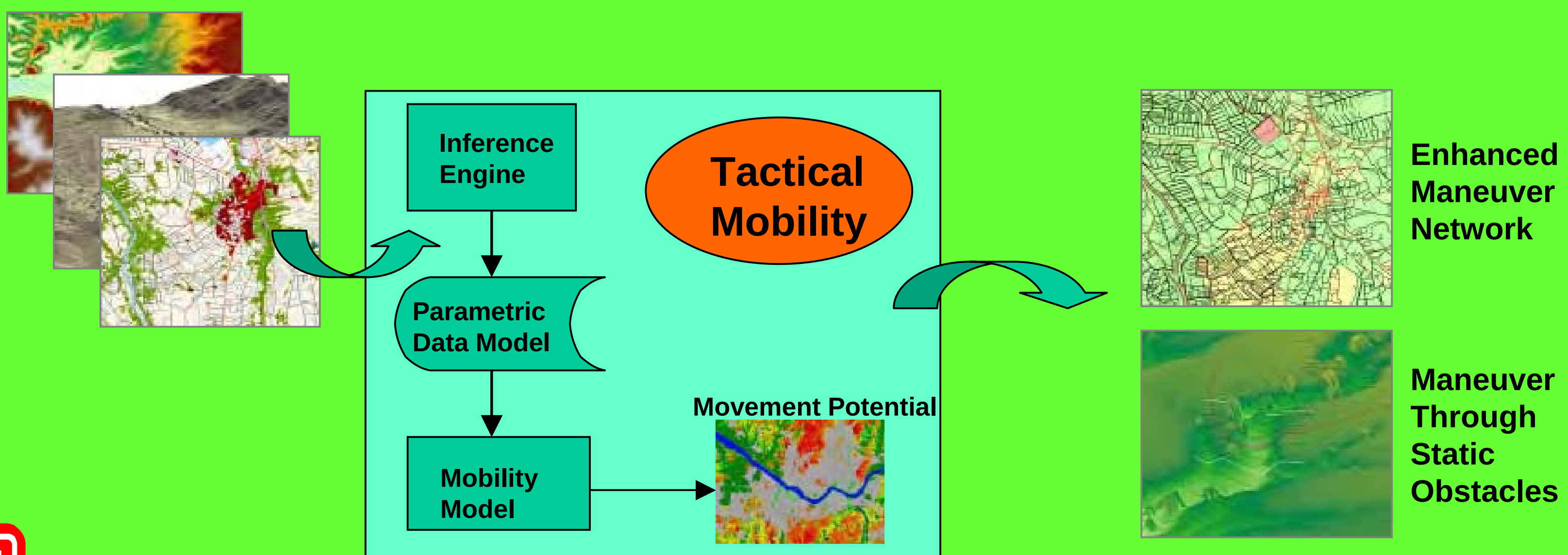
Challenges and Needs

- Unexploded ordnance (UXO)
- Countermine phenomenology
- **Terrain reasoning and awareness**



Battlespace Terrain Reasoning & Awareness - Tactical Mobility

Challenge: ***Provide transformation and inference algorithms for developing parametric databases from standard terrain data sources.***



Battlespace Terrain Reasoning & Awareness - Tactical Mobility

***Challenge:* Provide transformation and inference algorithms for developing parametric databases from standard terrain data sources.**

- **FOC-03-06: Situational Understanding. Must provide precision geospatial terrain environment information layers (modifiable digital overlays), which support cognitive and dynamic mission planning/rehearsal ….**

- **FOC-10-01: Understand the Battlespace Environment . Commanders at all levels must know how the environment, across the full range of natural and man-made elements, will impact their operations, as well as the operations of the enemy, and be able to use this knowledge to gain military advantage.**

Challenges and Needs

- Unexploded ordnance (UXO)
- Countermine phenomenology
- Terrain reasoning and awareness
- **Sediments**

Watersheds

Rivers, reservoirs and wetlands

Harbors and coastal areas

Sediments

Challenge: **Characterize and quantify suspended materials**

Multiple frequencies are required to estimate size distribution of a known suspended material type.

A multi-frequency system is operational for oceanic plankton characterization

Can a similar system be developed for heterogeneous suspended materials?

Sediments

Challenge: Determination of depth and characterization of bottom material

Acoustic-based hydrographic surveys are frequently confounded by "fluidized mud"

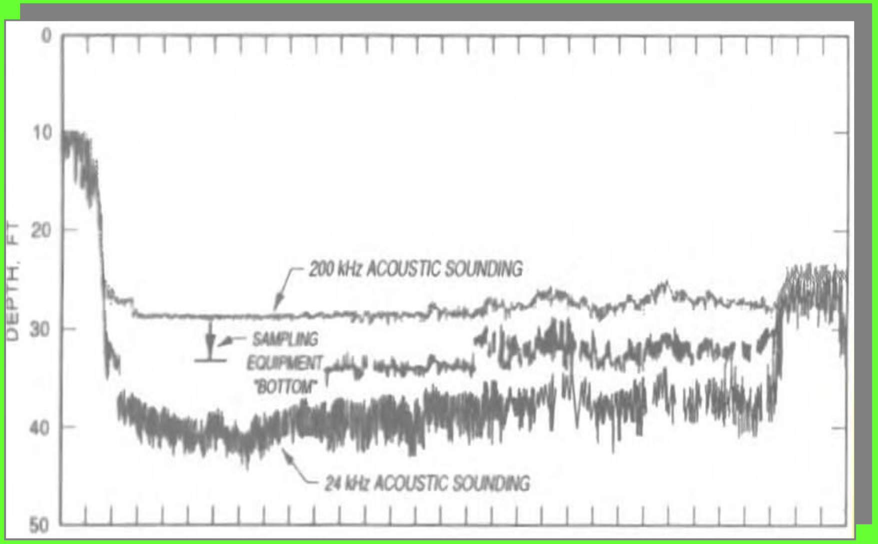
The automated bottom detection algorithm of using standard hydrographic frequency (~200kHz) show poor agreement with physically navigable depth in these low-density sediment areas.

This creates problems for navigation condition surveys, and planning and monitoring dredging activities.

Sediments

Challenge: Determination of depth and characterization of bottom material

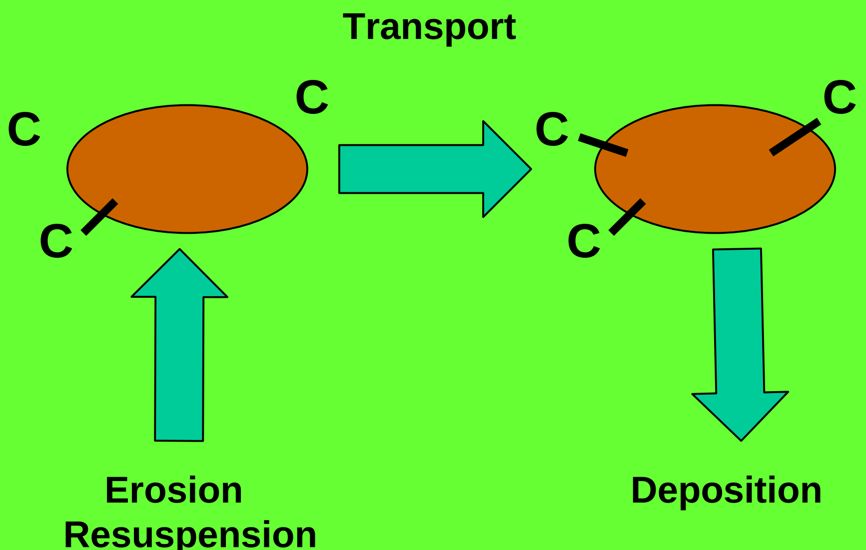
“When the upper sediment layer is not well consolidated, the three major depth measurement methods used in the Corps (sounding pole, lead line, and acoustic echo sounding) will generally not correlate with one another, or perhaps not even give consistent readings from one time to the next when the same type of instrument or technique is used” (Corps Engineer Manual 1110-2-1003 Hydrographic Surveying, 2001).



Sediments

Challenge: **Determination of depth and characterization of bottom material**

Metals and contaminants associate
with colloids, clays, and organic sediments



Sediments

Challenge: Determination of depth and characterization of bottom material

Contaminated dredged material must be confined and treated…

Deposition in reservoir inflow and littoral, and riverine sediments impact environmental quality…

Current methods for assessing the potential for contamination are costly and imprecise

Challenges and Needs

- Unexploded ordnance (UXO)
- Countermine phenomenology
- Terrain reasoning and awareness
- Sediments
- **Aquatic vegetation**

Submerged Aquatic Vegetation

Challenge: ***Quantify biomass and discriminate species***

Narrow single beam, single frequency echo sounders have proven effective for detecting submersed aquatic vegetation and characterizing canopy height and relative density….biomass quantification and species discrimination have so far been elusive.

Submerged Aquatic Vegetation

Challenge: Quantify biomass and discriminate species

Attempts to use target strengths as predictors of biomass are only good within an order of magnitude. Target strengths measured for different species of estuarine submersed vegetation are widely overlapping along with canopy heights and density. The use of spatial pattern recognition techniques may be the way to go for species discrimination since different monospecific stands exhibit different “patchiness” characteristics.

Submerged Aquatic Vegetation

Challenge: Mitigate the effects of submerged vegetation on hydrographic surveys

Submersed macrophytes, particularly seagrasses, are significant acoustical reflectors over a broad range of frequencies and as such can hide what is below the midsection of the canopy. This may include obscuring the true bottom in hydrographic surveys of harbors.

Submerged Aquatic Vegetation

***Challenge:* Mitigate the effects of submerged vegetation on mine detection**

Another aspect of 'seeing' through vegetation is mine detection in vegetated nearshore areas. Seagrasses are significantly stronger targets (higher reflective cross section) when viewed from the side than from the top. This confounds the use of side scan sonar systems to find objects on the bottom – a common tool for mine detection.

Challenges and Needs

Summary

- Unexploded ordnance (UXO)
- Countermine phenomenology
- Terrain reasoning and awareness
- Sediments
- Aquatic vegetation

Appendix 3c

Jim Simmons

Biomimetic design and the technological implications of animal sonar

James A. Simmons
Brown University

May 4, 2004

Office of Naval Research

National Science Foundation

National Institute of Mental Health

DoD University Research Instrumentation Program

Brown University

Novel features of transduction and processing used by echolocating bats and dolphins in relation to man-made methods can be discerned when appropriate observations are made on the animals. When this is done, the wideband, FM biosonar system used by bats reveals a whole cascade of differences in basic design having little or no overlap with engineered systems in transduction, waveform representation, signal-processing, or display.

(1) In its capacity as a sonar receiver, the bat’s auditory receiver utilizes a more radical concept of parallel processing than anything manifested in even the most advanced man-made systems.

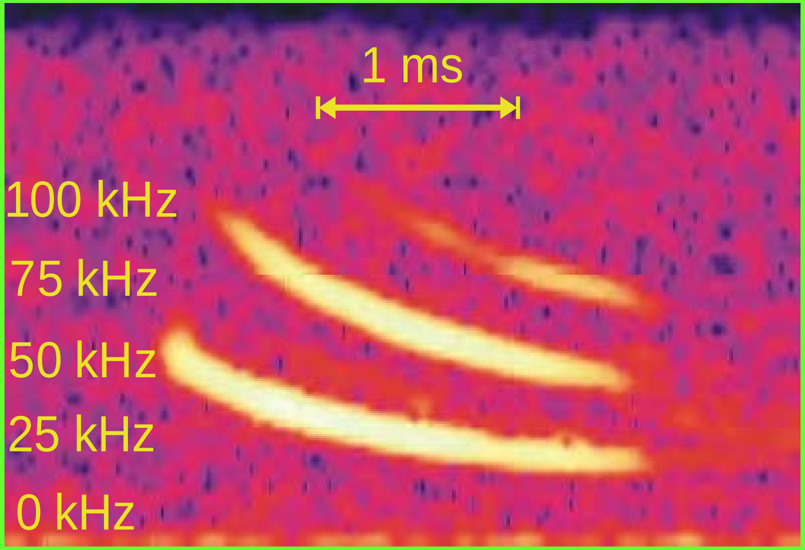
(2) The organization and interplay of time-domain and frequency-domain elements used by bats yields a higher degree of systems integration than would be expected from examination of any of the elements in isolation.

(3) Knowledge of this system can be exploited to design unconventional man-made systems, but not if the goal is merely to emulate animal performance with conventional digital signal-processing devices.

(4) The efficiency of object imaging and classification in echolocation derives from the parallelism inherent throughout the entire system, not just from a particular choice of target features, which implies designing the system from the ground up.

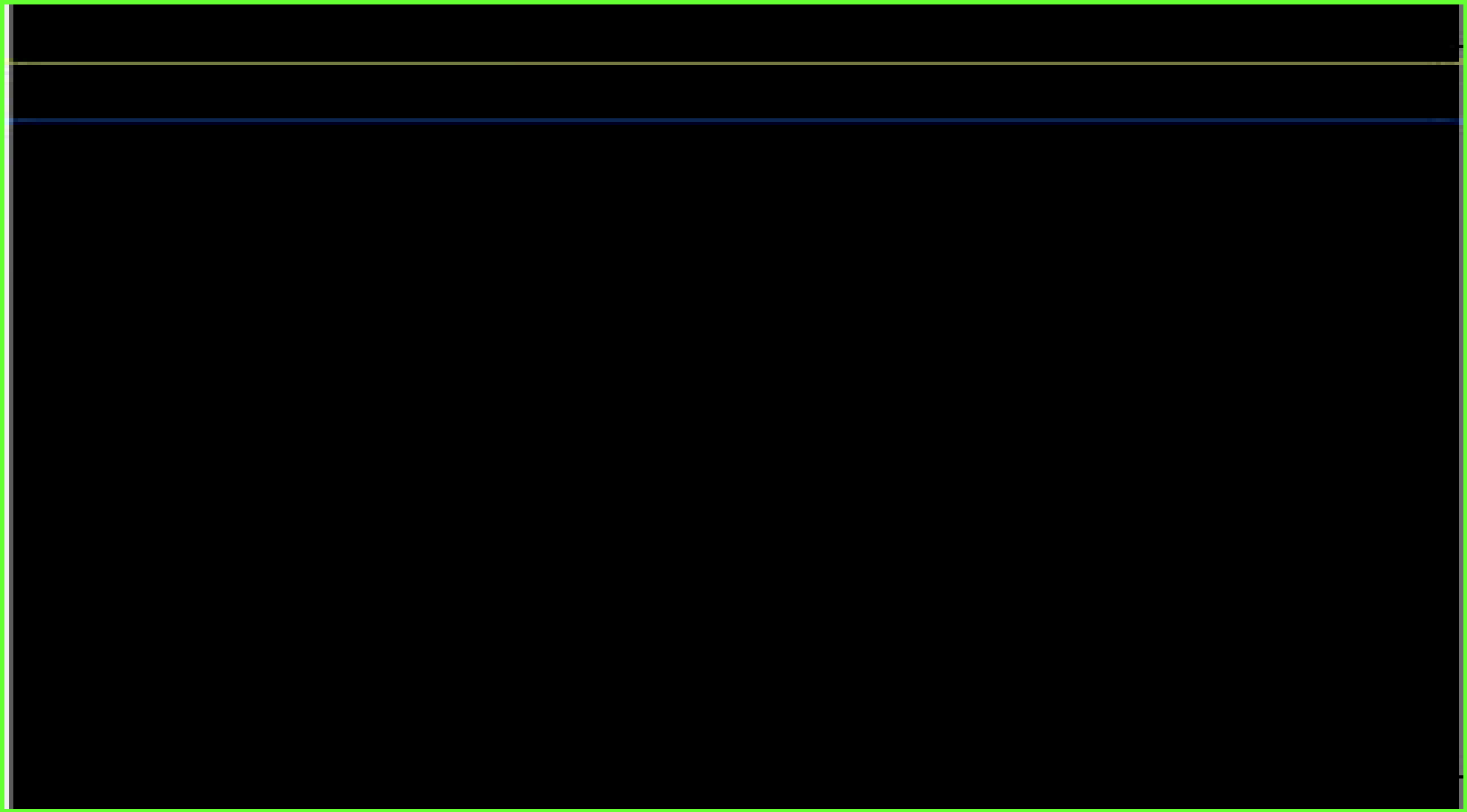
A pollen-and-nectar bat (*Glossophaga*) performing a sonar-guided docking maneuver to feed at a small opening in a hummingbird feeder.

A protracted sonar-guided dogfight between two big brown bats (*Eptesicus*).



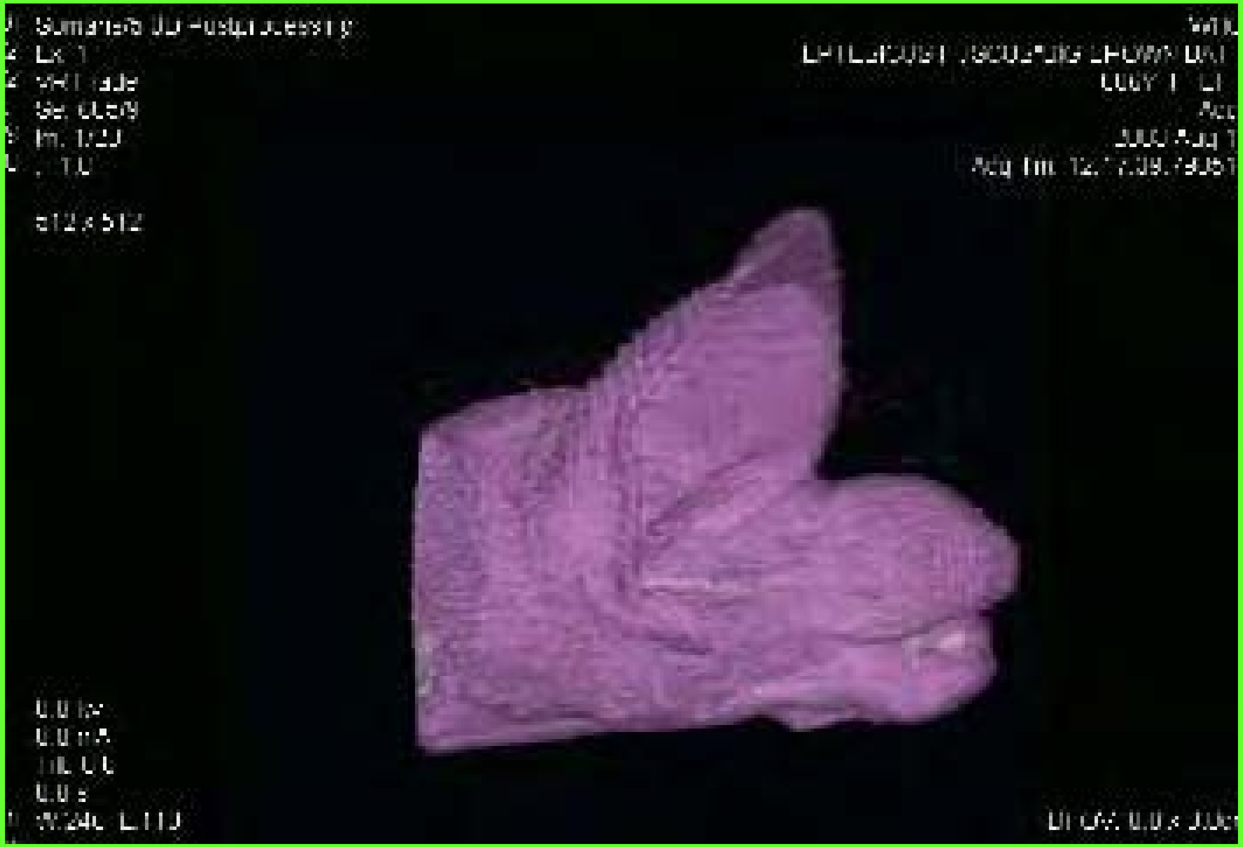
The echolocating big brown bat, *Eptesicus fuscus*, is a common North American insectivorous species in the family Vespertilionidae. It broadcasts frequency-modulated (FM) sonar sounds in the range of 20 to 100 kHz.

The most familiar behavior of echolocating big brown bats is aerial interception of flying insects.

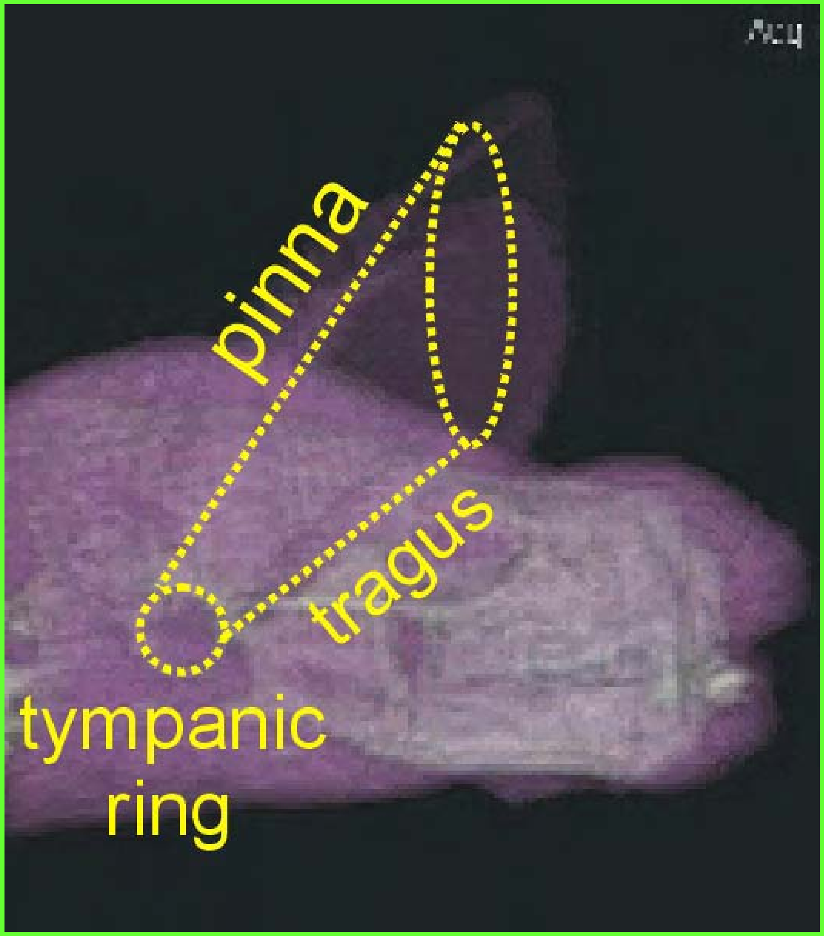


Slowing down the recording shows how successive sounds in the pursuit sequence of FM sonar signals become shorter in duration and faster in repetition-rate as the bat approaches the target.

The bat's external ears act as receiving antennas. This rotating CT Scan image shows their complicated shape, which creates directional sensitivity used to determine target elevation. (CT data from Darlene Ketten, WHOI)

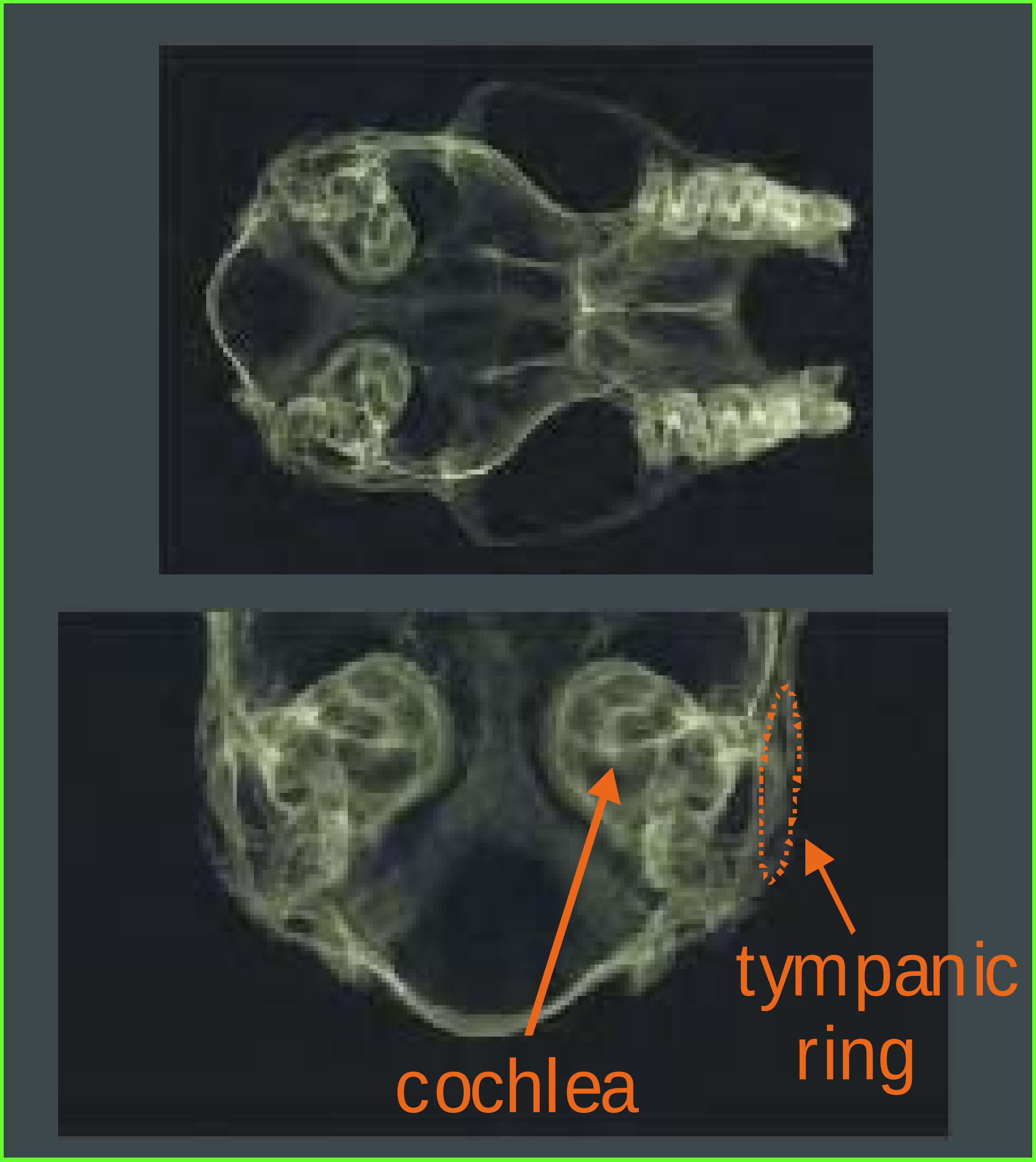


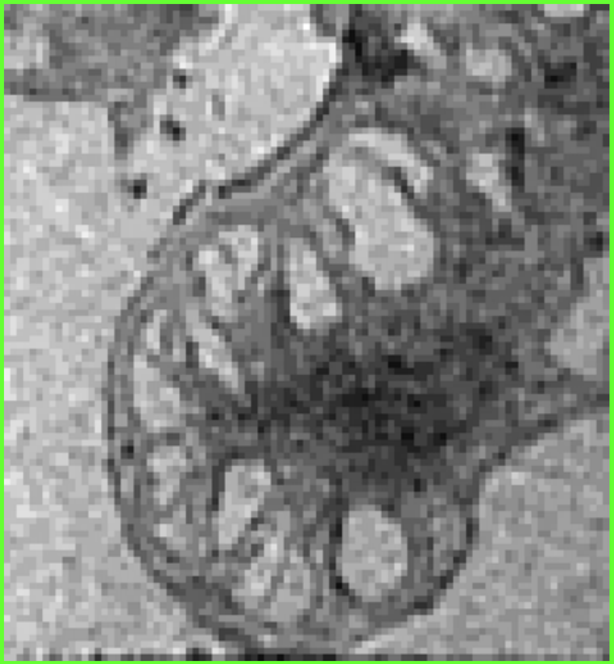
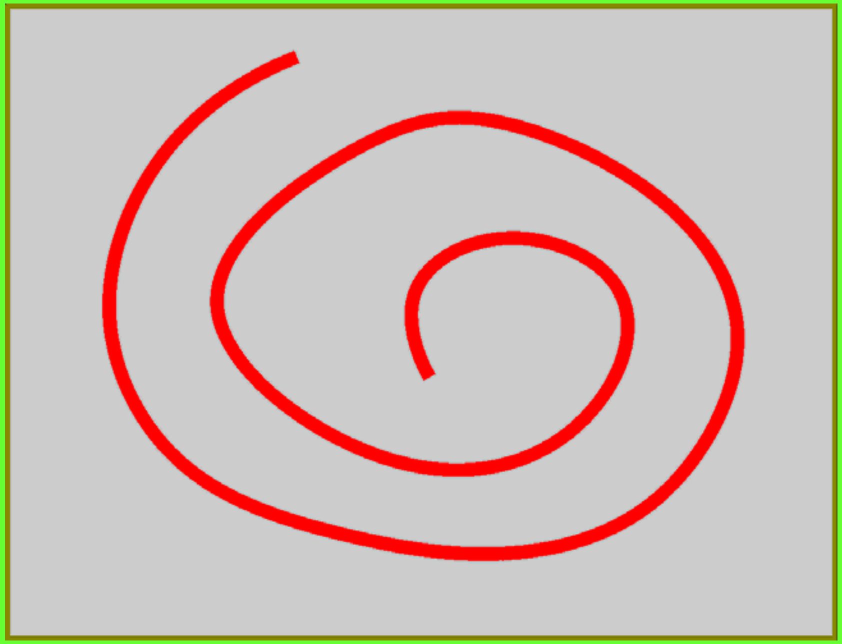
Fading the component of the image originating from low-density soft tissue exposes the relation between the external ear and the bony tympanic ring supporting the eardrum.



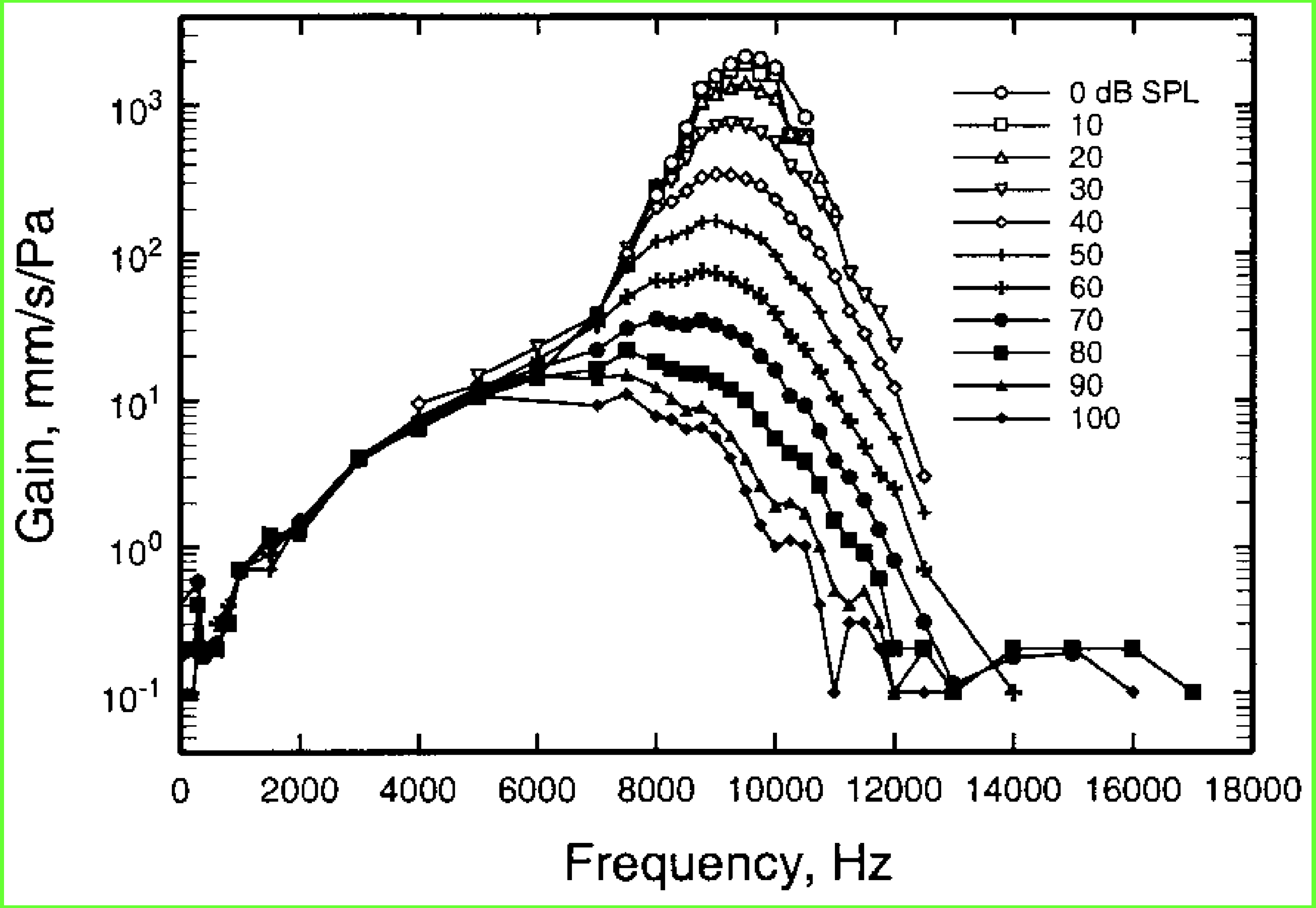
When viewed from the side, the bat’s external ear is approximately an obliquely truncated horn whose tapered cross-section aids in impedance matching from free-field sound to the eardrum.

Transduction takes place inside the spiral cochlea after sound is mechanically coupled from the eardrum to the cochlear fluid by the middle-ear system.

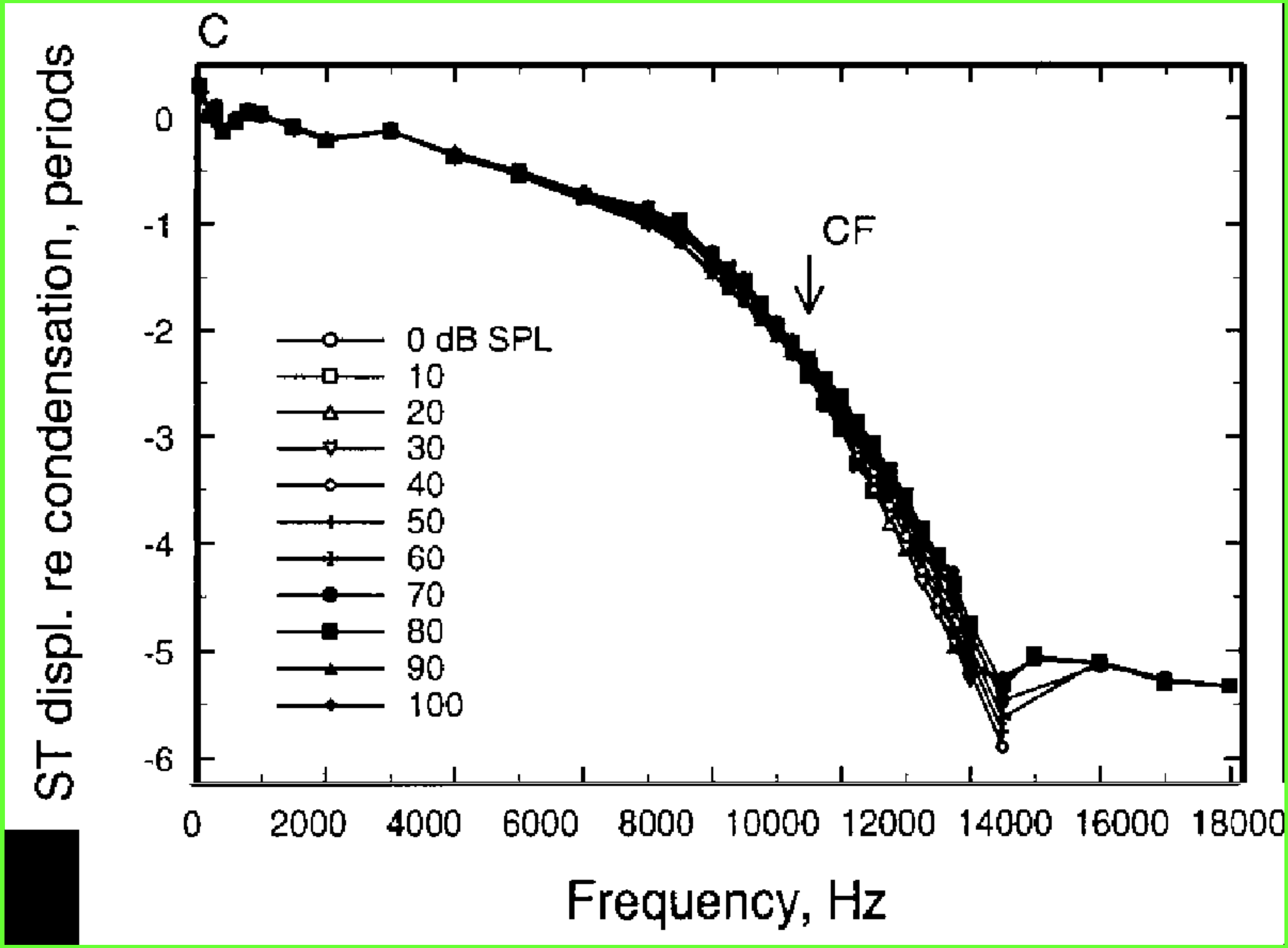


Inside the cochlea, the spiral organ of Corti filters the FM sweeps into a succession of frequency segments. At left is a microMRI cross-section of the cochlea of the big brown bat (from O.W. Henson & Mirriam Henson). At right is the reconstructed spiral of the big brown bat's cochlea from serial MicroMRI images (Rothholtz, 1999). The length of the basilar membrane is about 12 mm.



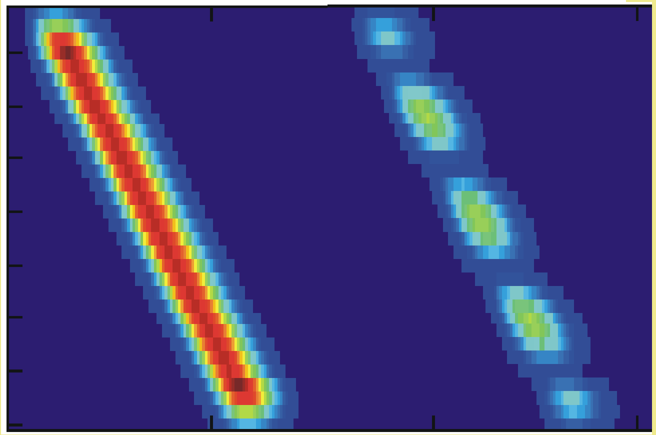
Each of the ~1000 bandpass filters in the cochlea has level-dependent gain. This plot shows the mechanical gain in frequency response curves at the ~10 kHz point on basilar membrane of the chinchilla (Ruggiero, *et al.* 2000). In effect, the inner ear receives weaker sounds with higher-Q filters that have more gain.



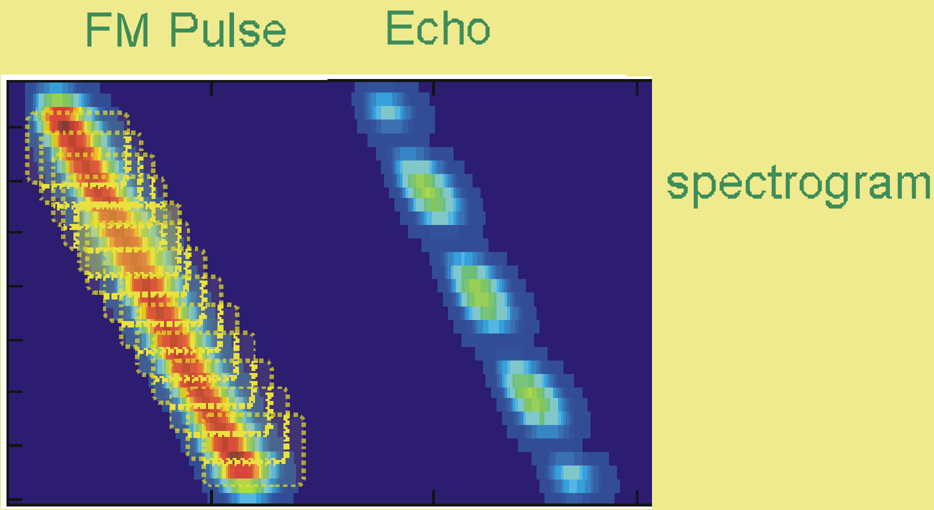
Signals being transduced at different amplitudes nevertheless have constant phase characteristics. This plot shows the coherent alignment of traveling-wave cycles across different amplitudes at the ~10 kHz point on the basilar membrane of the chinchilla (Ruggiero, *et al.* 2000).

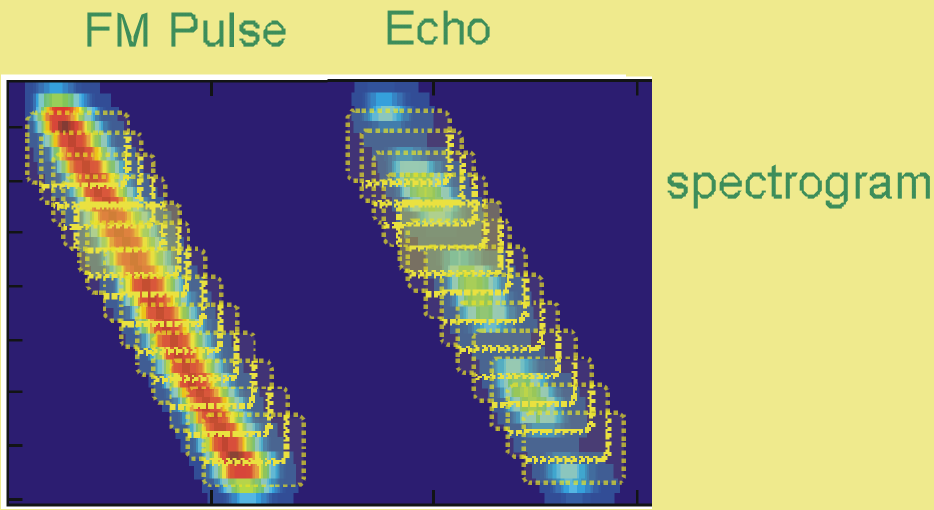
Analyzing the reception and processing of biosonar echoes is done in two passes--first, in terms of signal-processing, and, second, in terms of neural circuits.

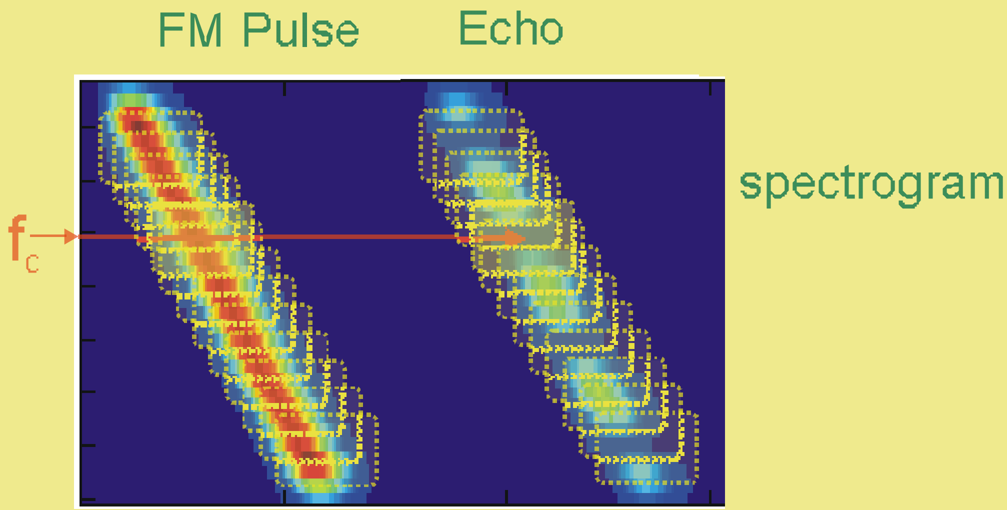
FM Pulse Echo



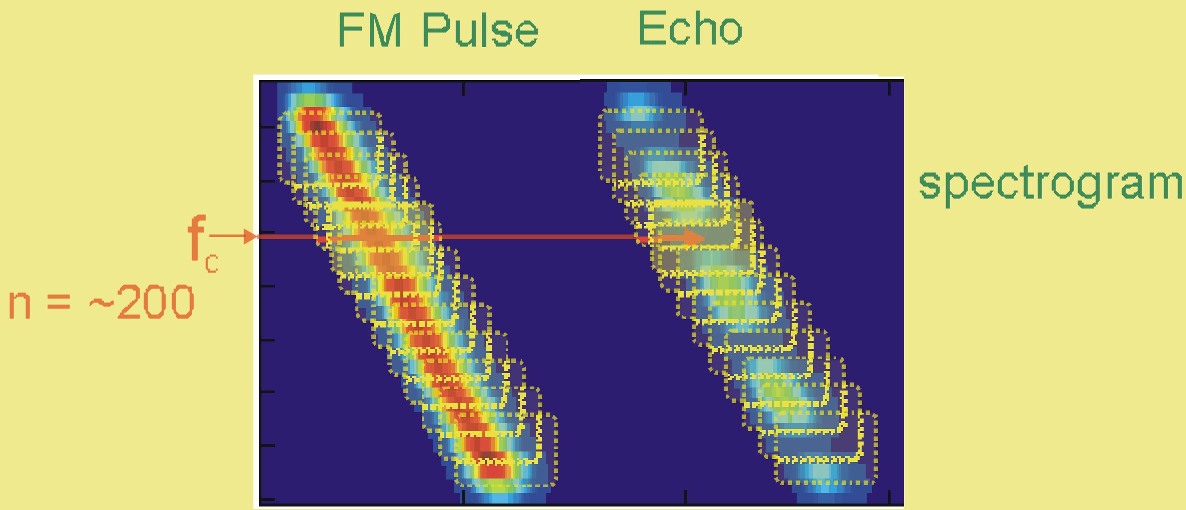
spectrogram


FM Pulse
Echo
spectrogram

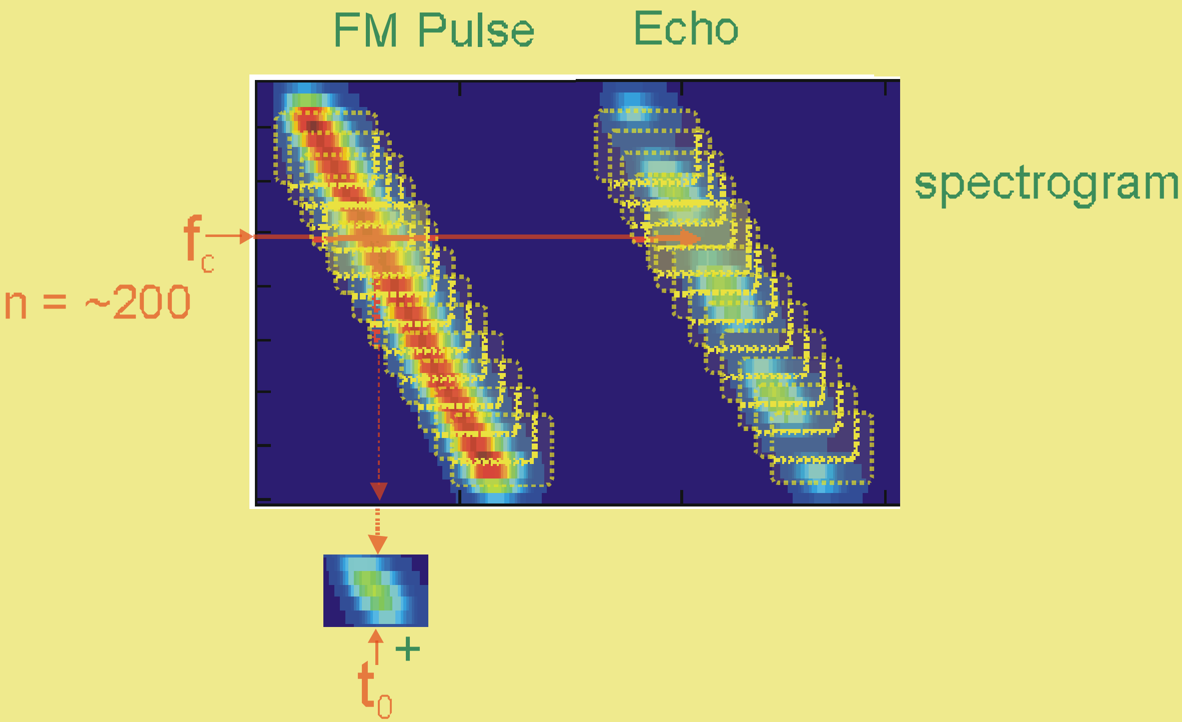

FM Pulse
Echo
spectrogram

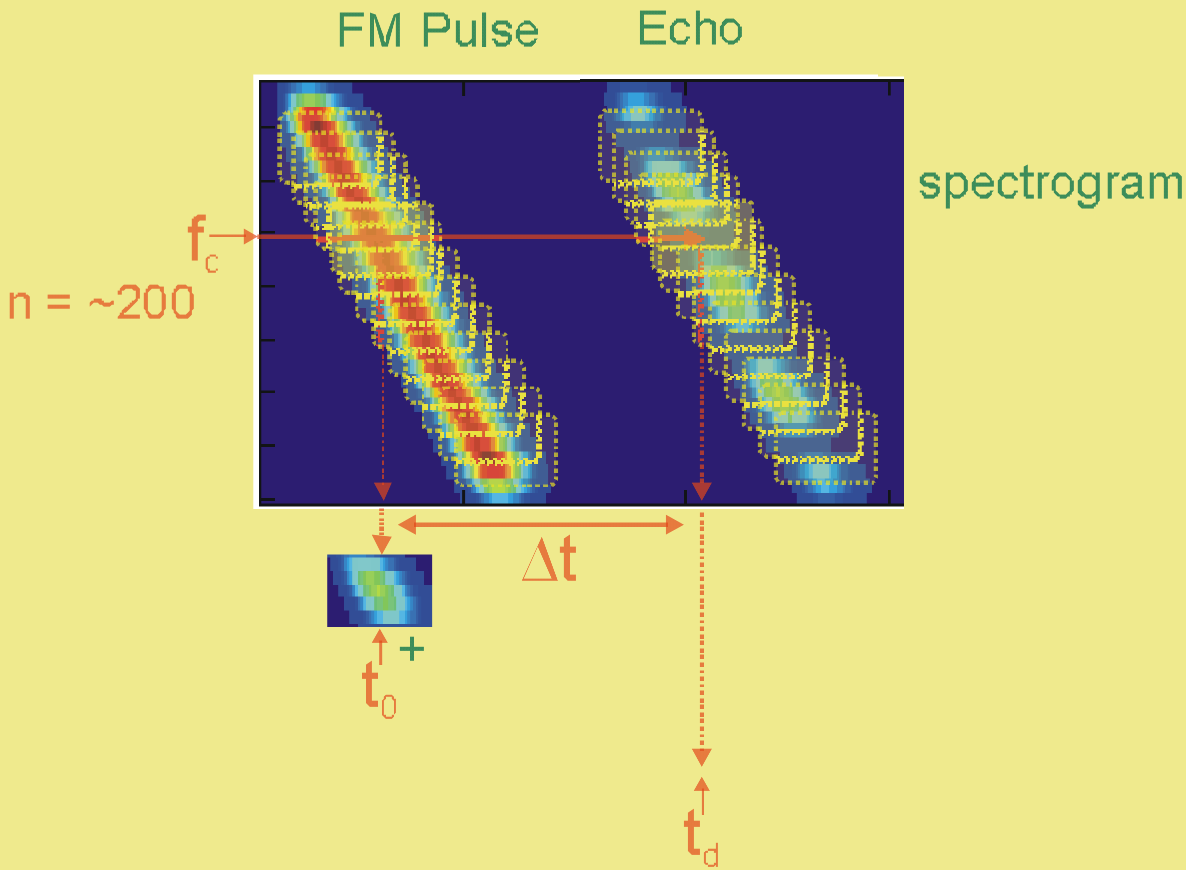


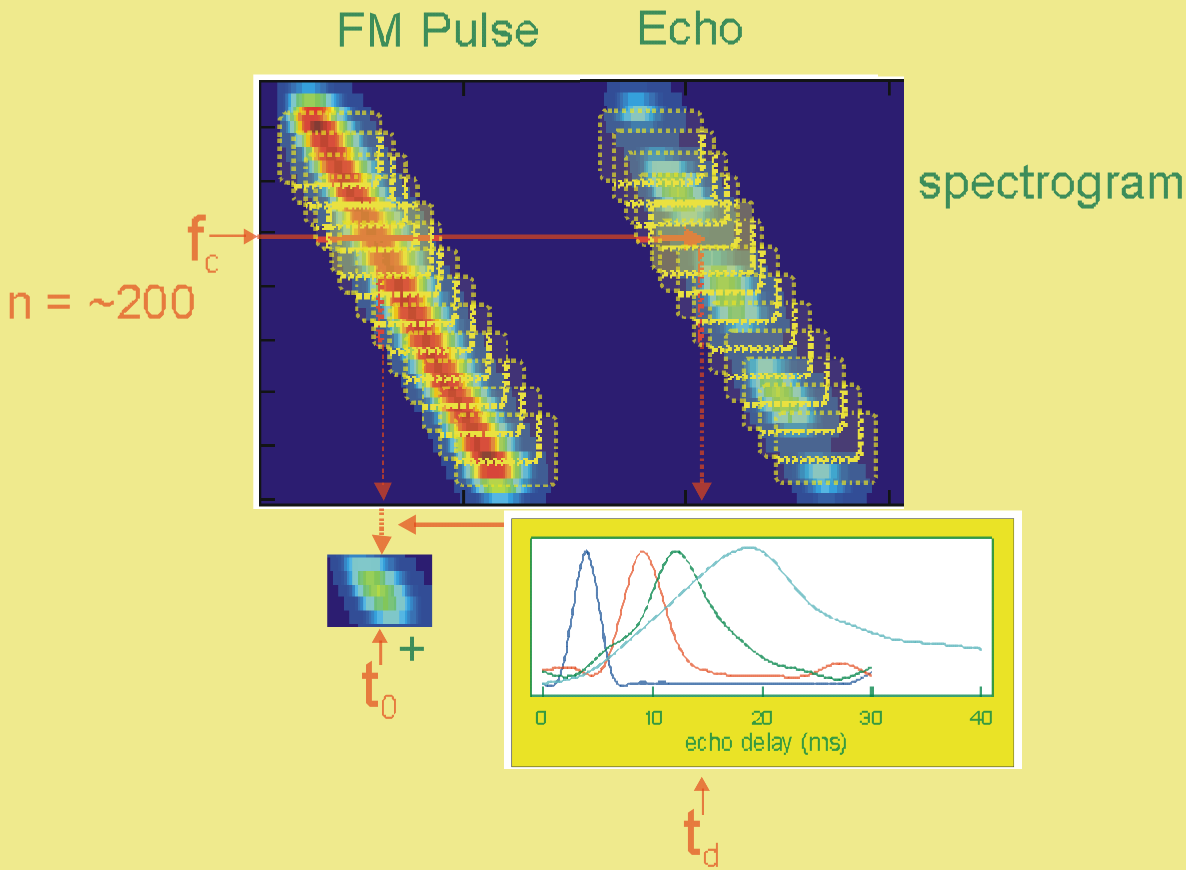
FM Pulse
Echo
spectrogram
f_c



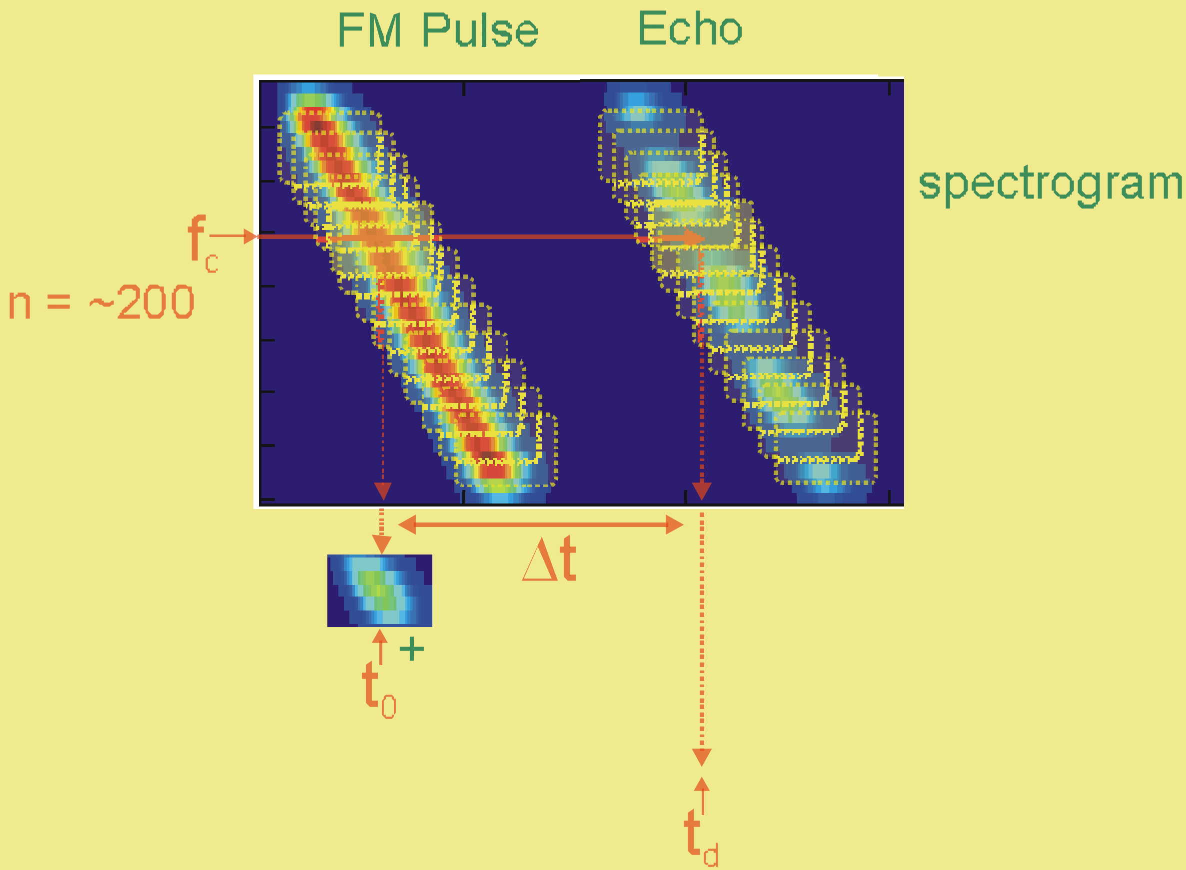
FM Pulse
Echo
spectrogram
f
c
n = ~200

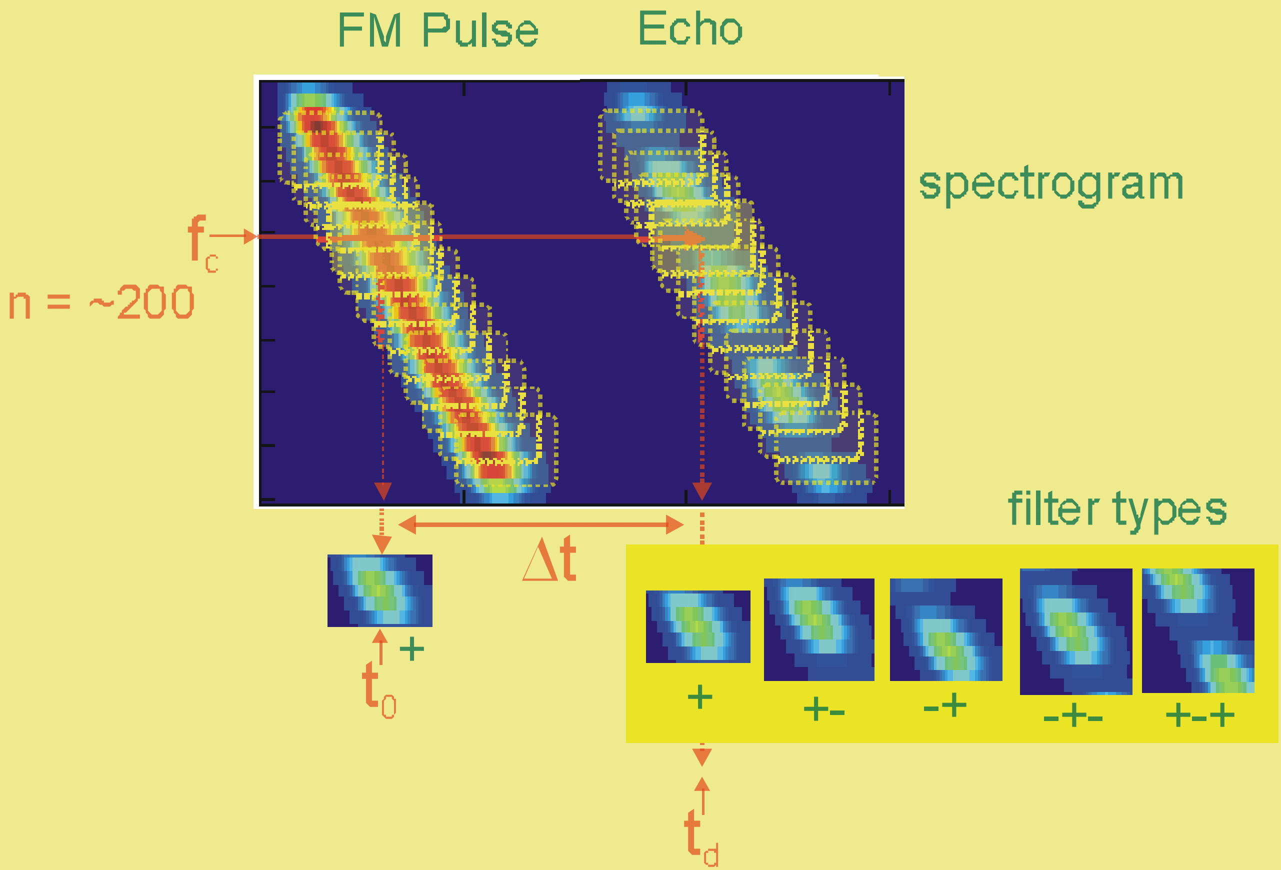

FM Pulse
Echo
spectrogram
f_c
n = ~200
+
t_0


FM Pulse
Echo
spectrogram
fc
n = ~200
Δt
+
t0
td

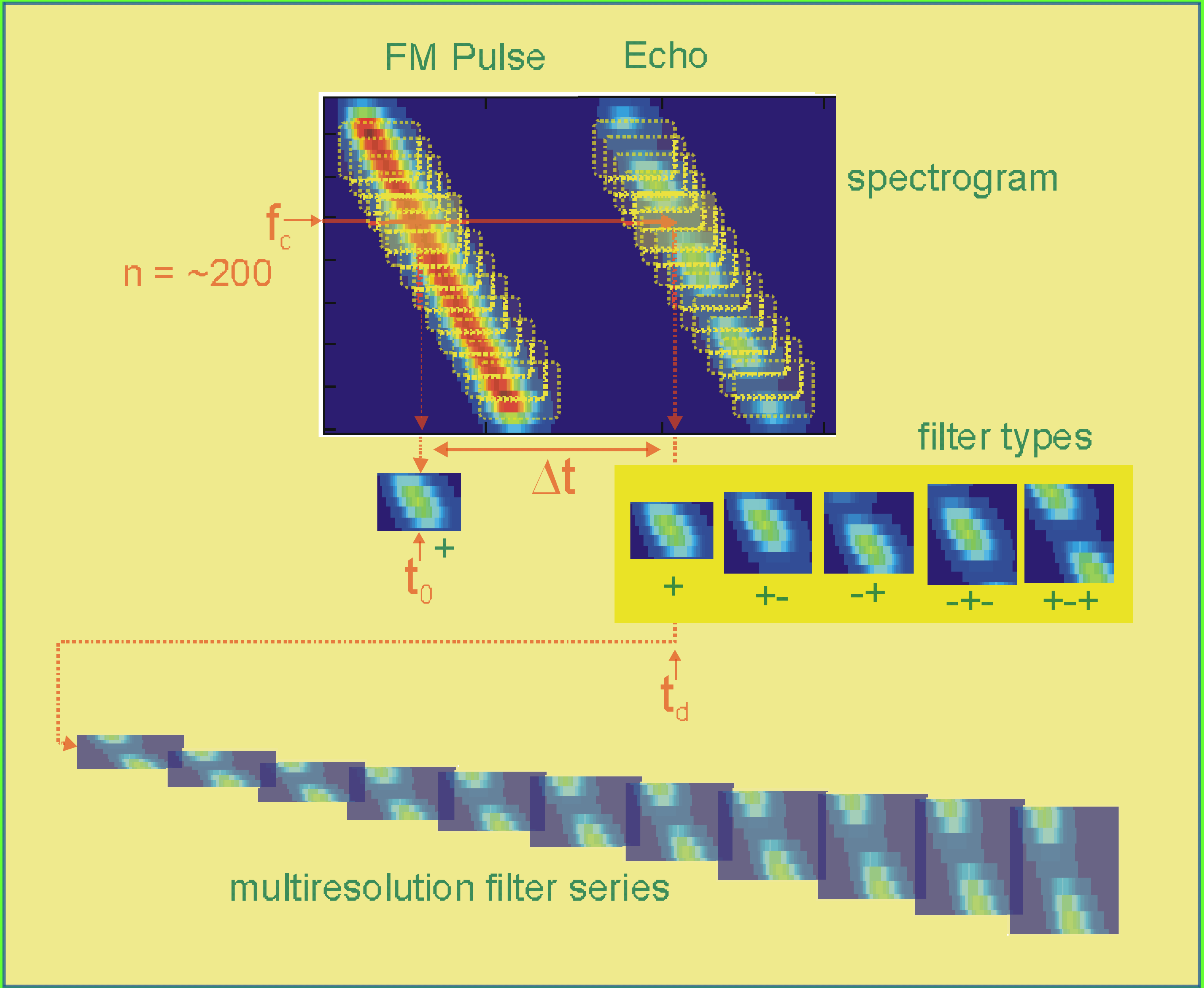


FM Pulse
Echo
spectrogram
f
c
n = ~200
+
t
0
0
10
20
30
40
echo delay (ms)
t
d

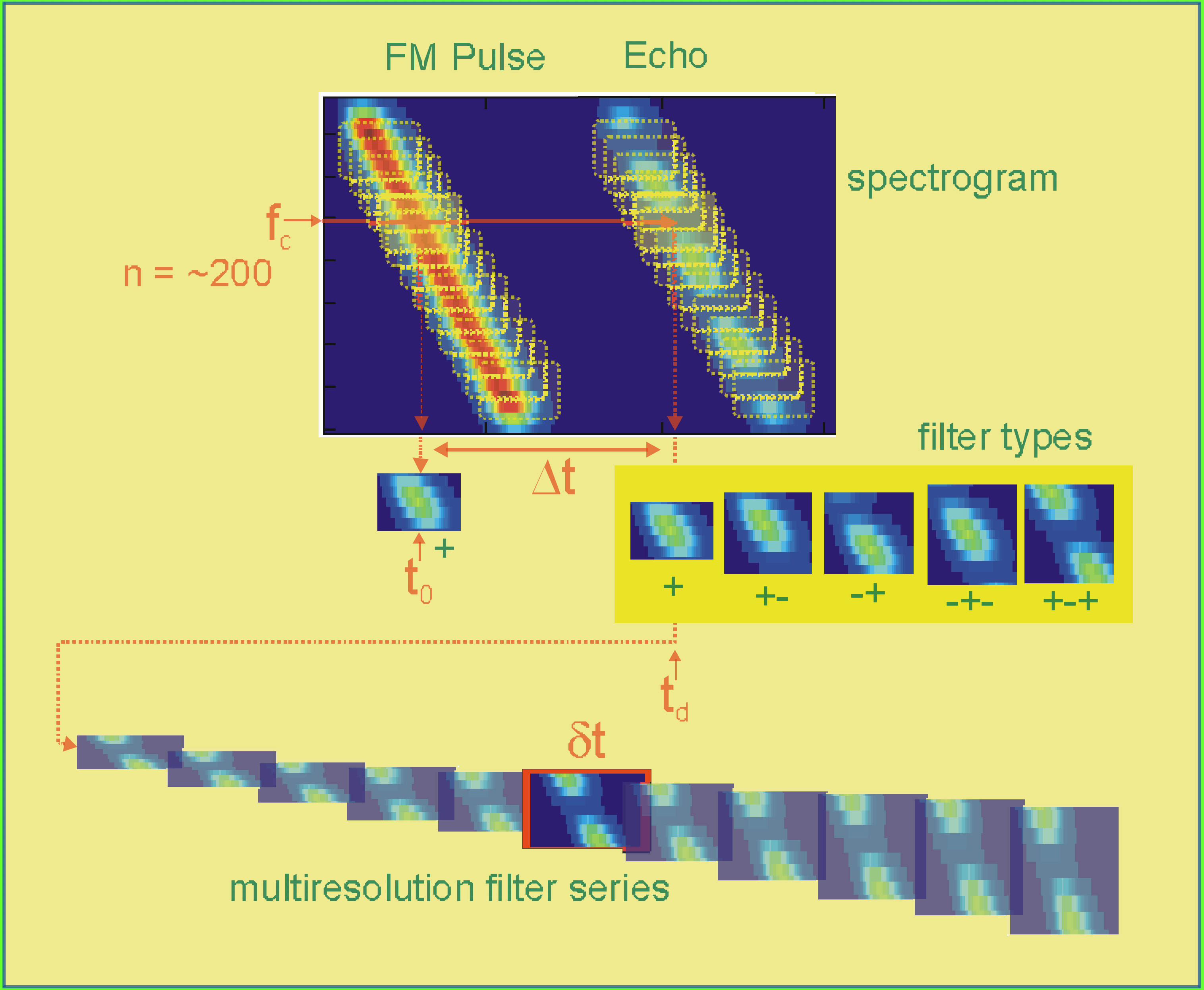

FM Pulse
Echo
spectrogram
f
c
n = ~200
Δt
+
t
0
t
d



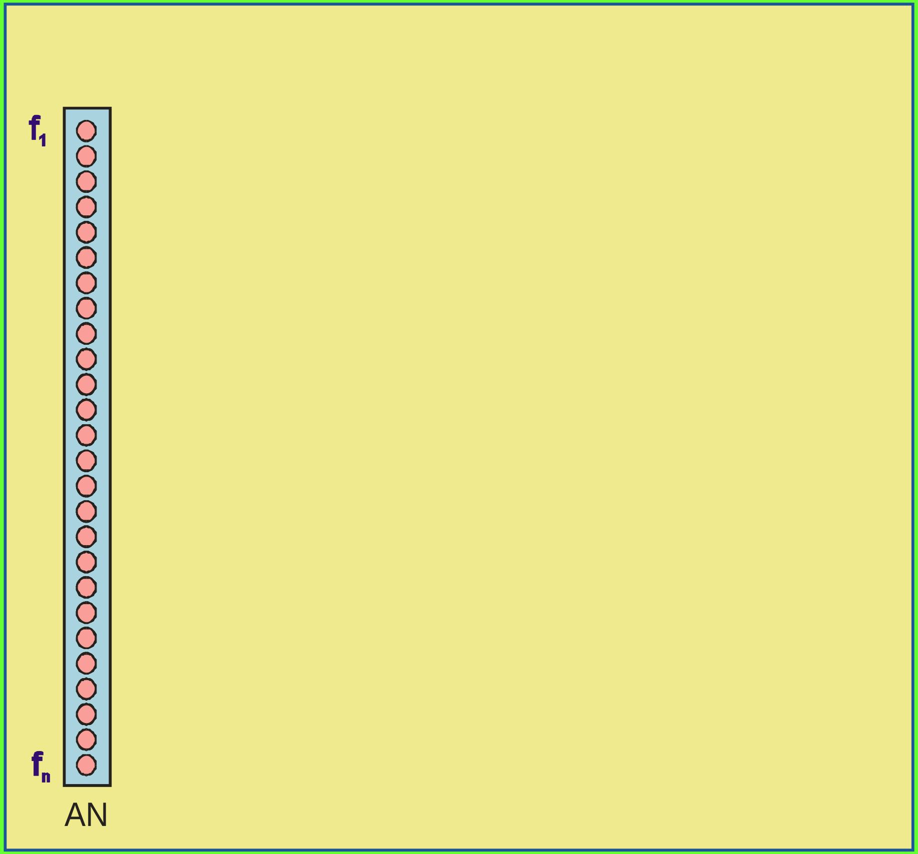
FM Pulse
Echo
spectrogram
f_c
n = ~200
Δt
t_0
+
filter types
+
+-
-+
-+-
+-+
t_d



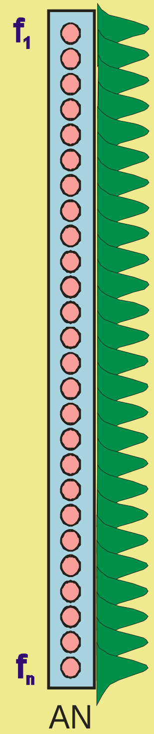
FM Pulse
Echo
spectrogram
f_c
n = ~200
Δt
t_0
+
filter types
+
+-
-+
-+-
+-+
t_d
multiresolution filter series

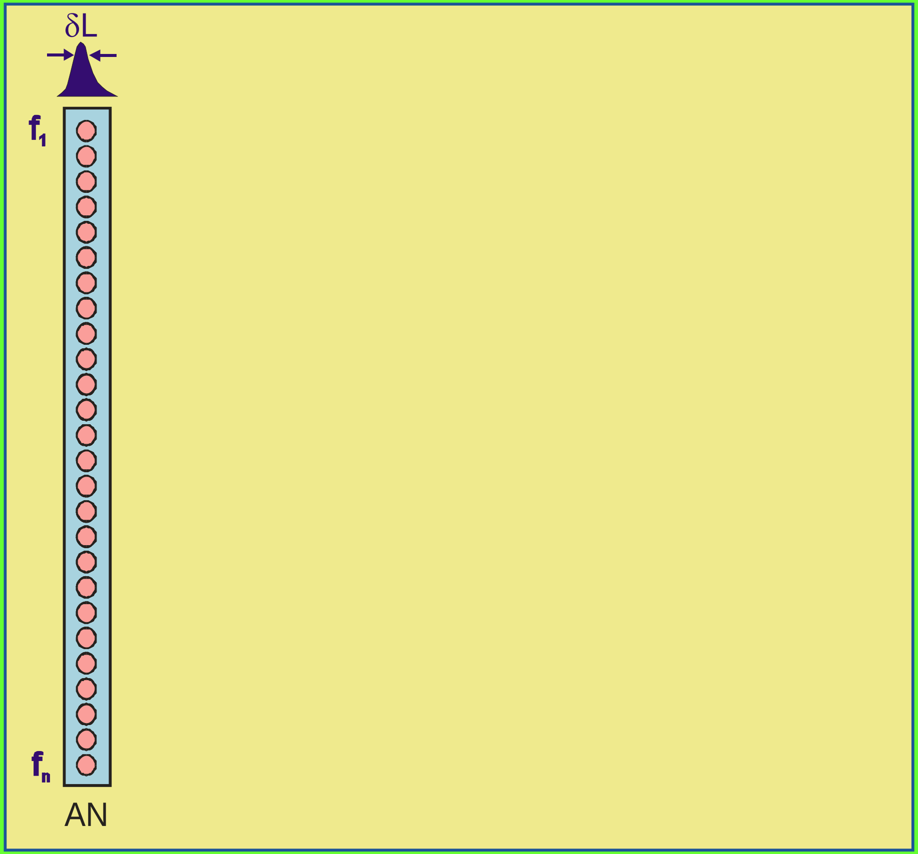

FM Pulse
Echo
spectrogram
f_c
n = ~200
filter types
Δt
+
t_0
+
+-
-+
-+-
+-+
t_d
δt
multiresolution filter series

Analysis of biosonar in terms of neural circuits begins with the filters of the cochlea.

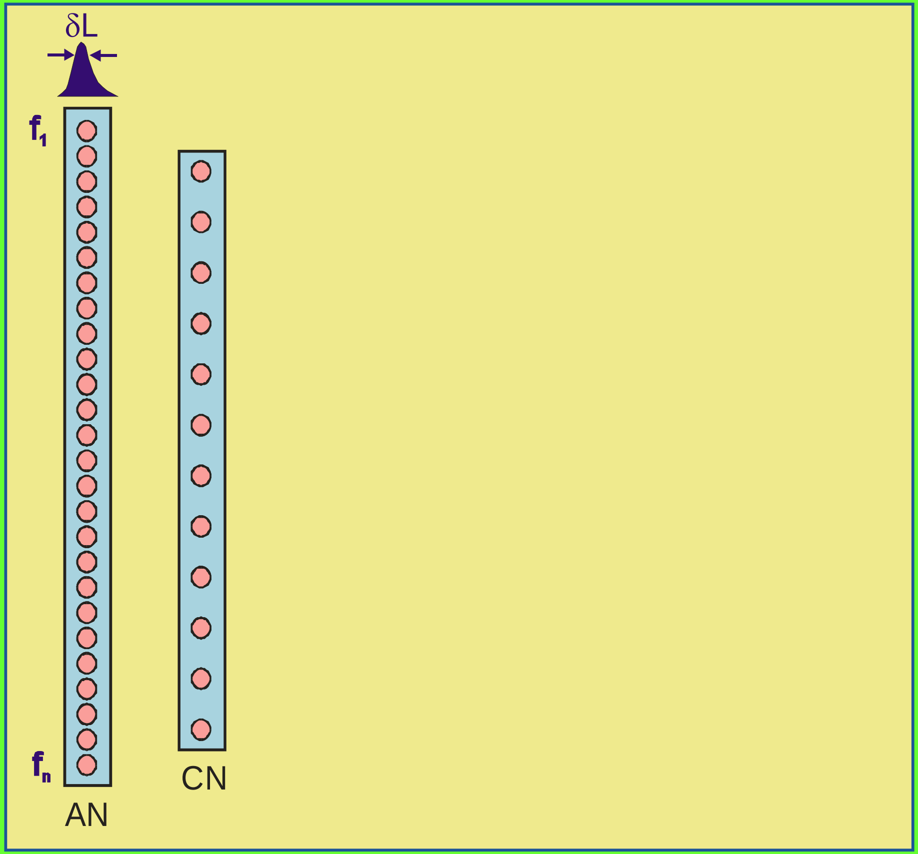


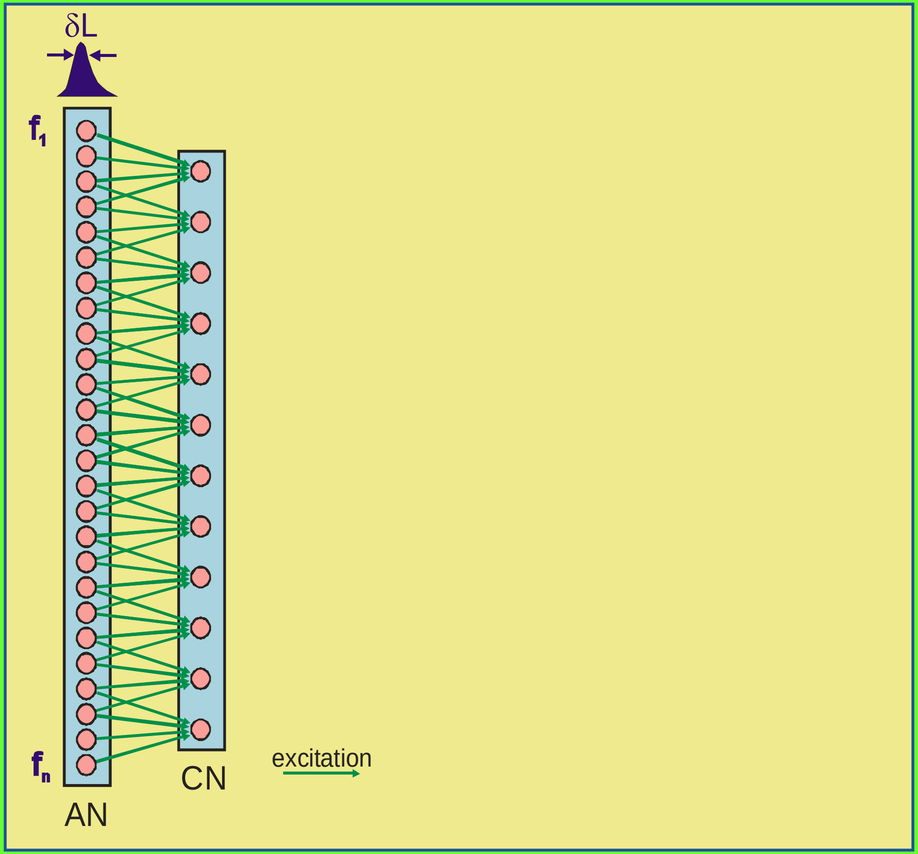
f_1
f_n
AN

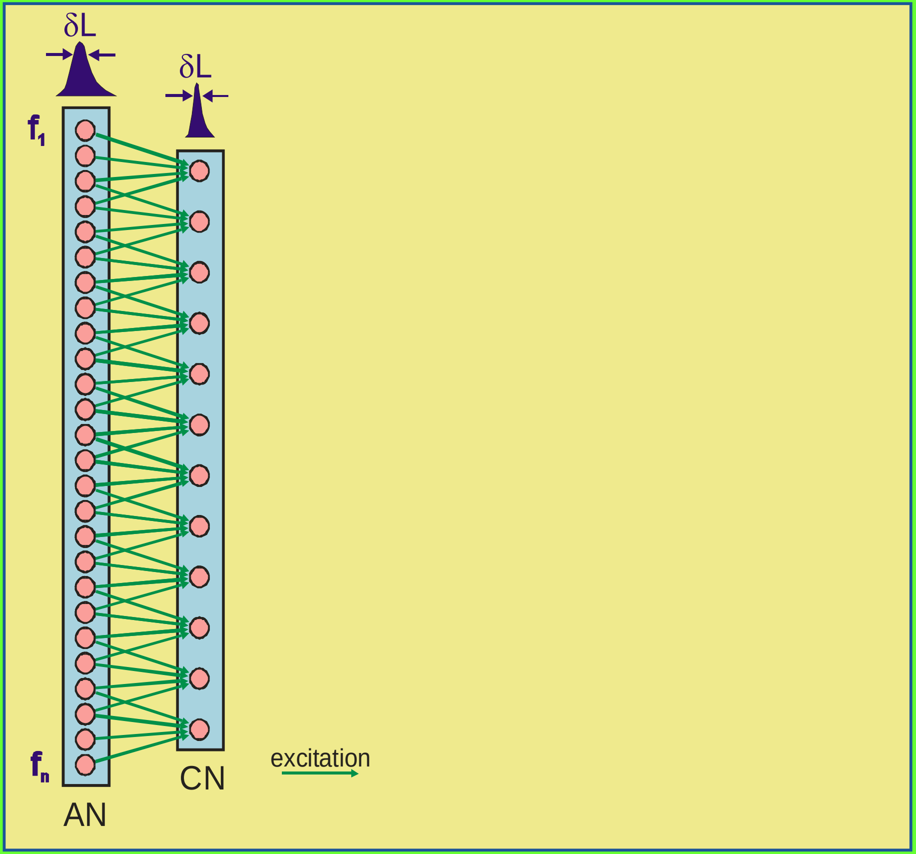

f1
fn
AN



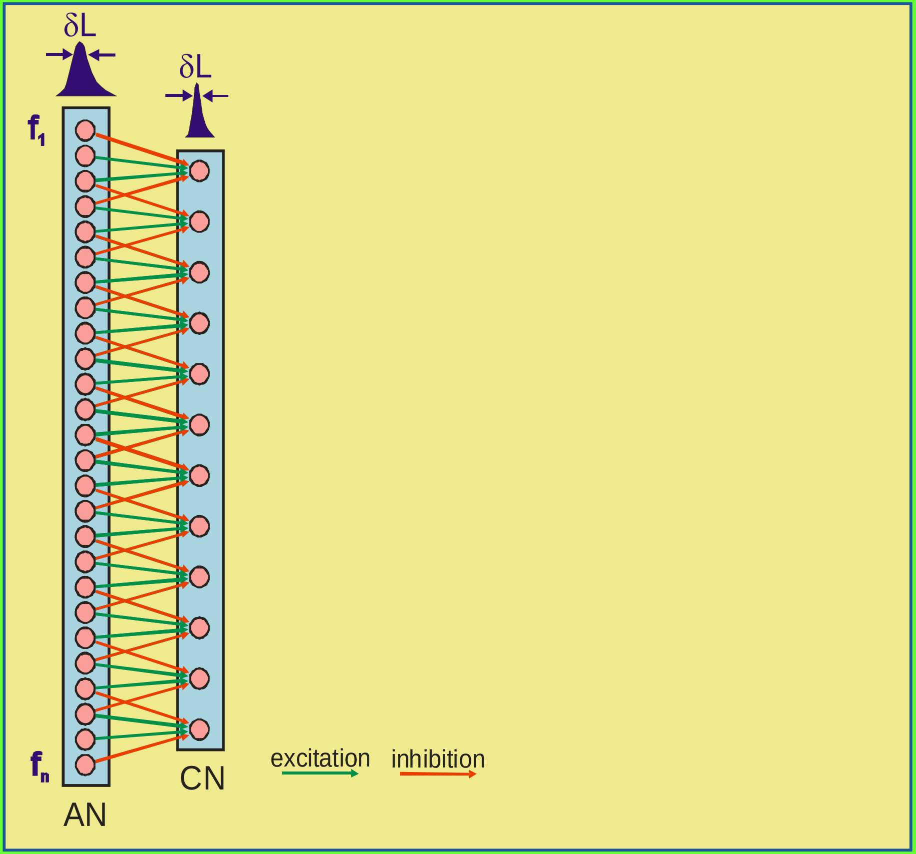
δL
f1
fn
AN


δL
f1
fn
AN
CN

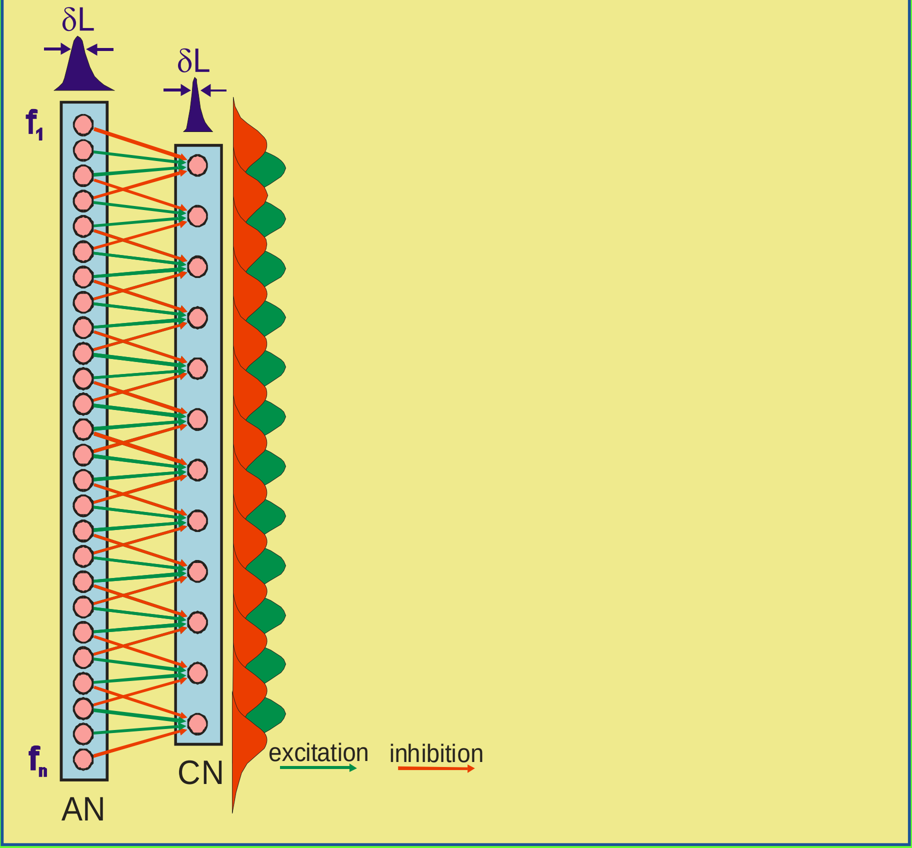

δL
f1
fn
AN
CN
excitation



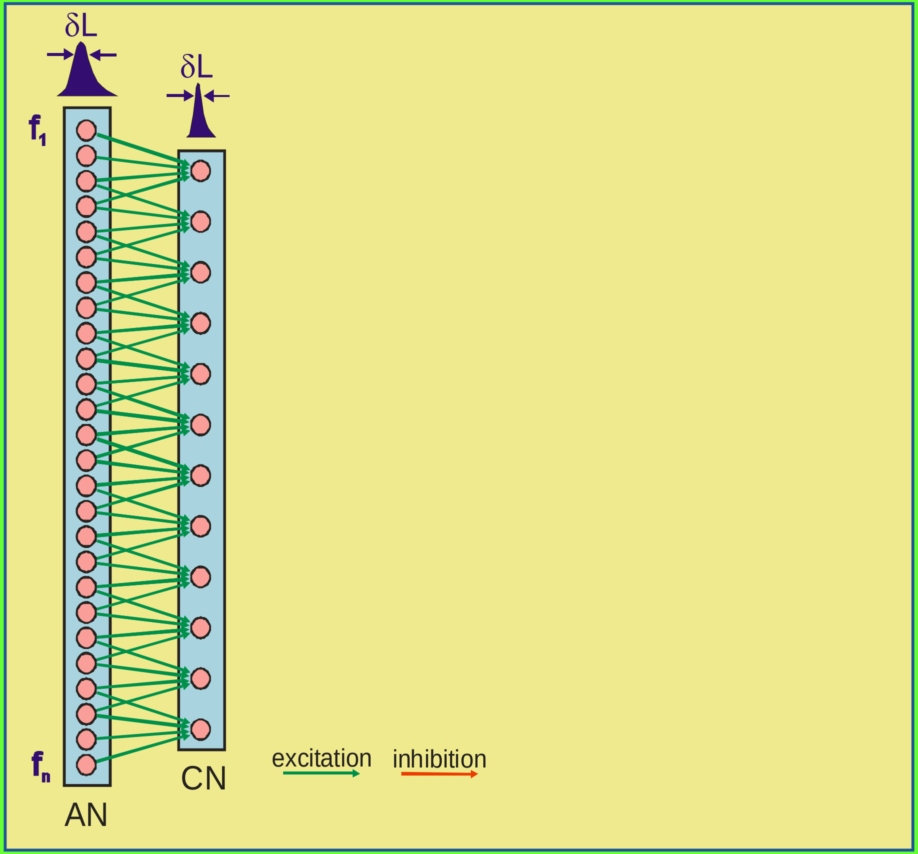
δL
δL
f_1
f_n
AN
CN
excitation



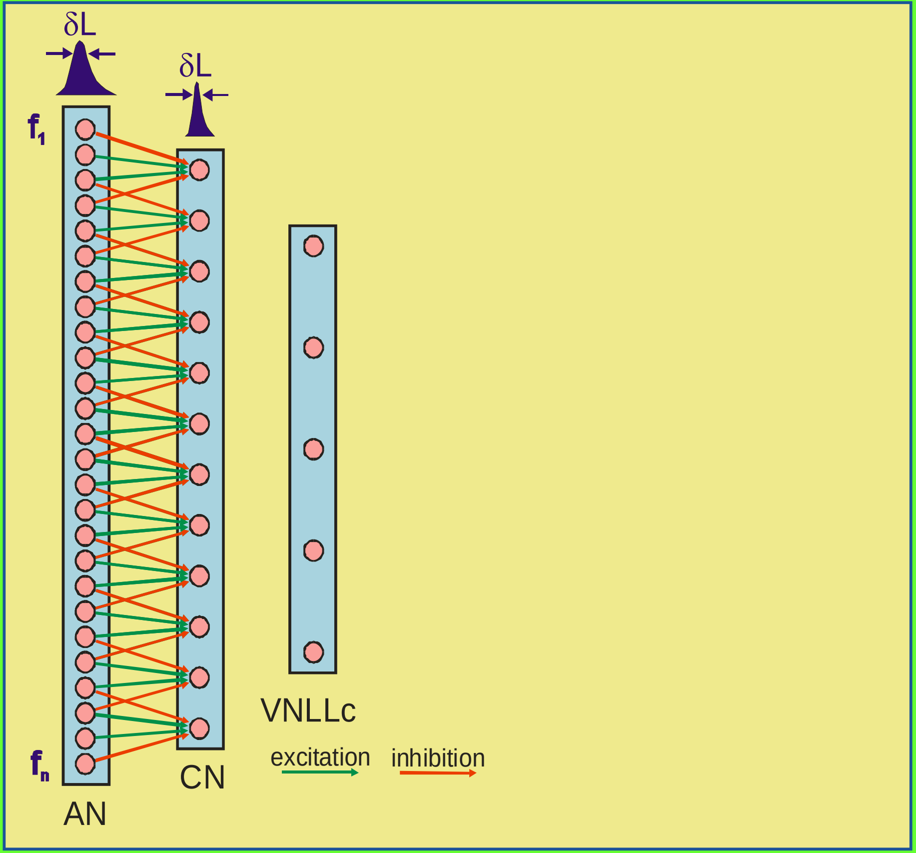
δL
δL
f_1
f_n
AN
CN
excitation
inhibition

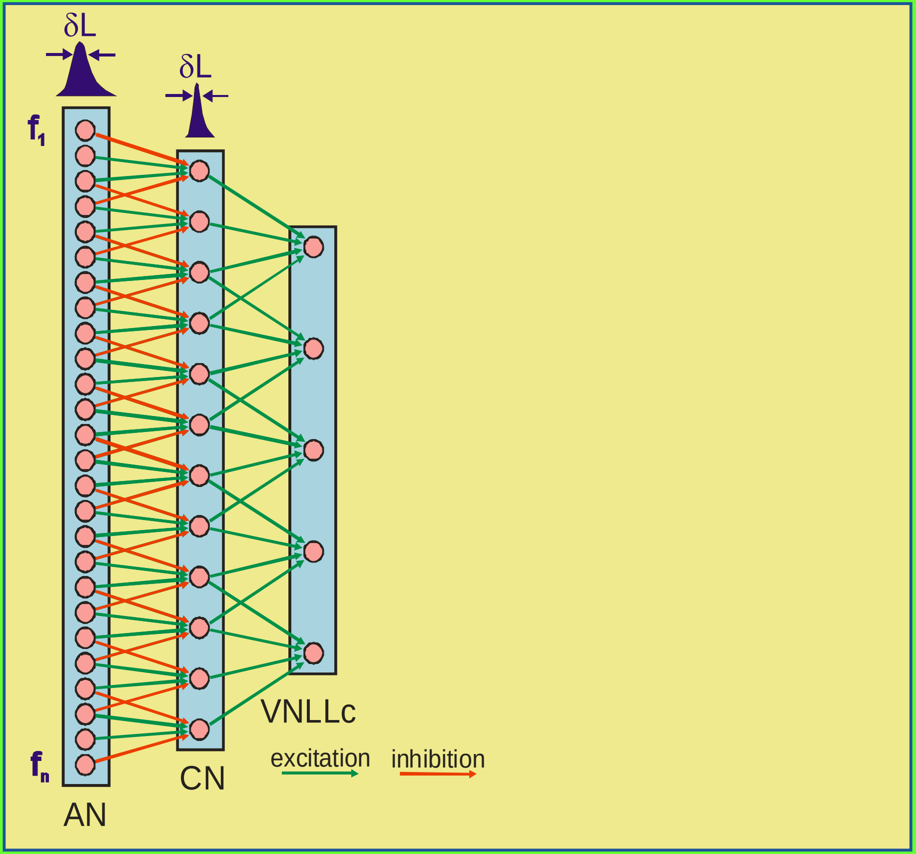


δL
δL
f1
fn
AN
CN
excitation
inhibition

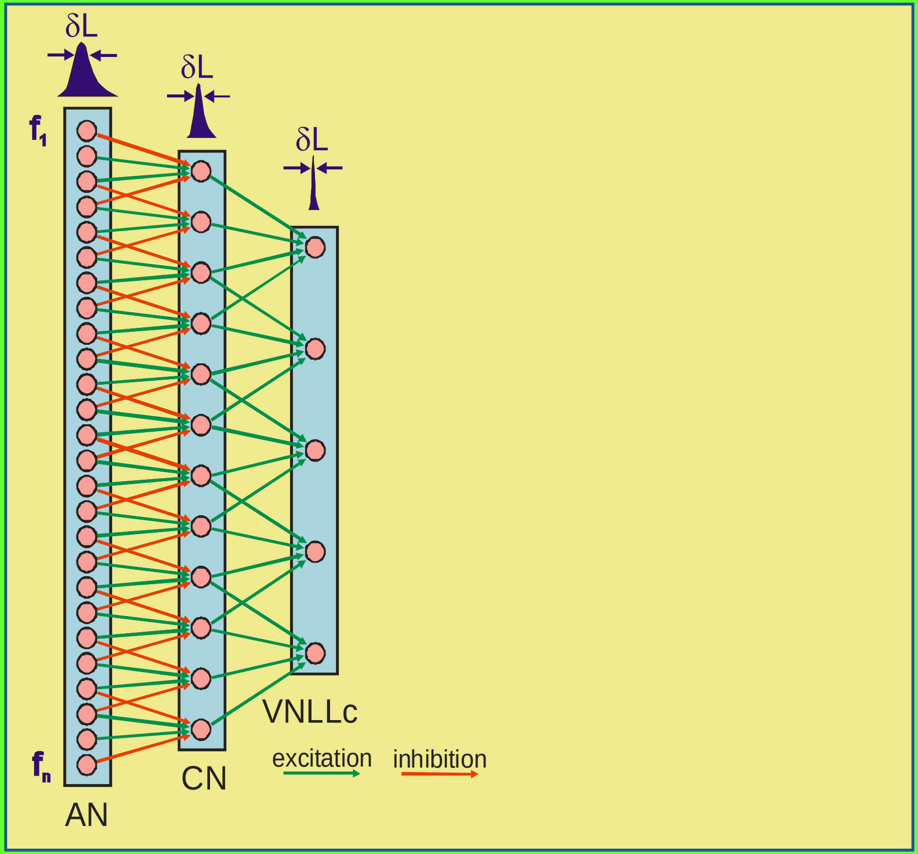


δL
δL
f_1
f_n
AN
CN
excitation
inhibition

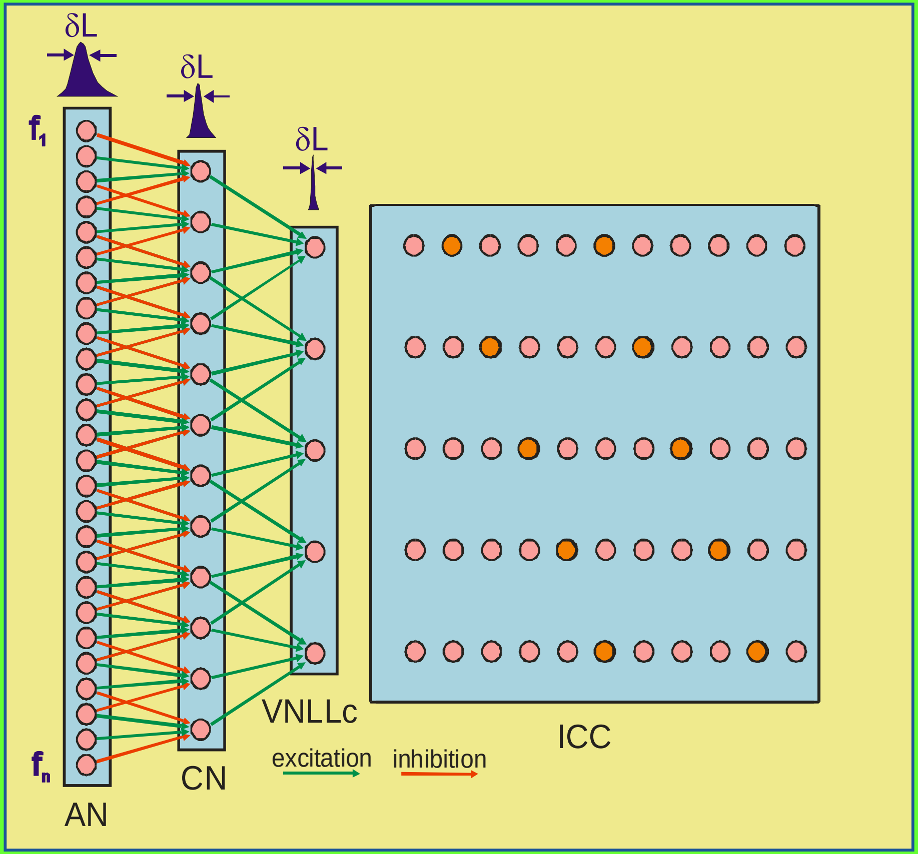

δL
δL
f1
fn
AN
CN
VNLLc
excitation
inhibition



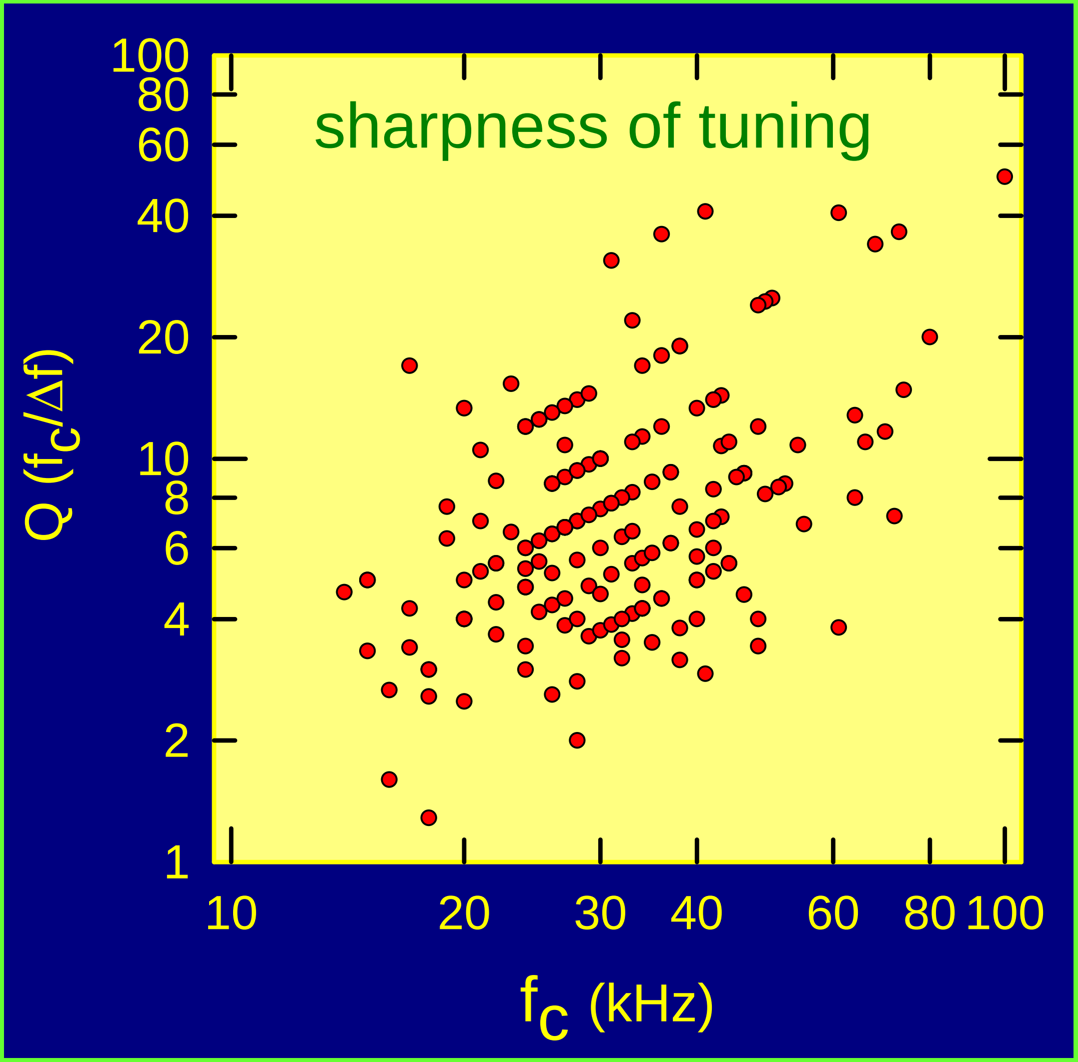
δL
δL
f1
fn
AN
CN
VNLLc
excitation
inhibition

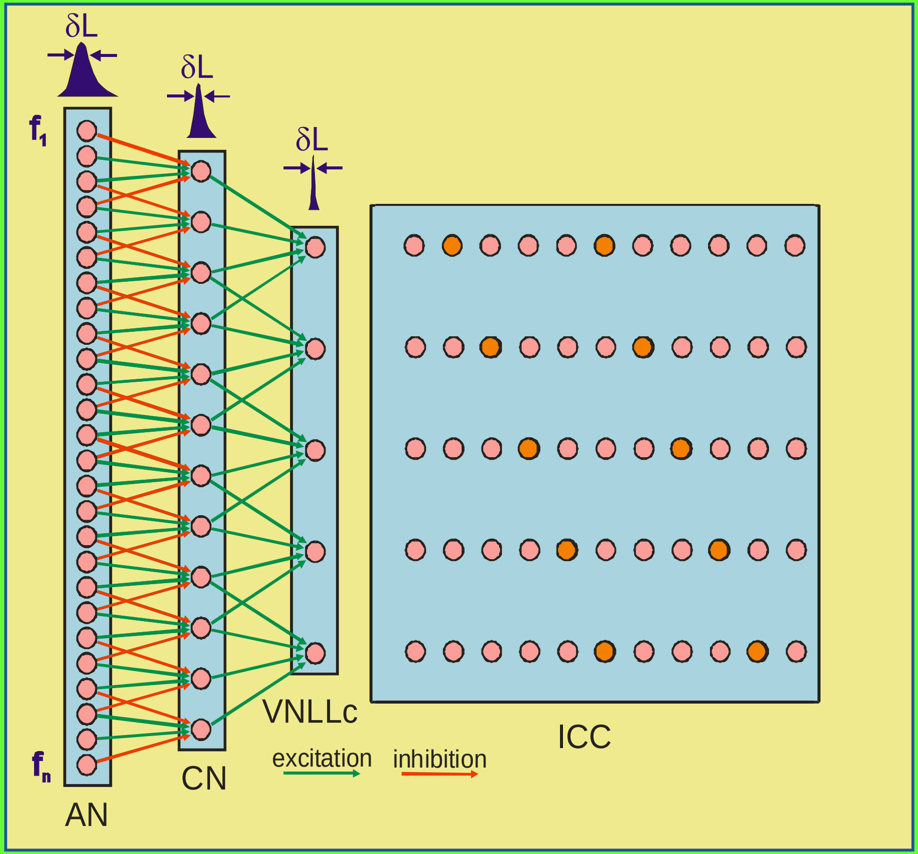


δL
δL
δL
f1
fn
AN
CN
VNLLc
excitation
inhibition

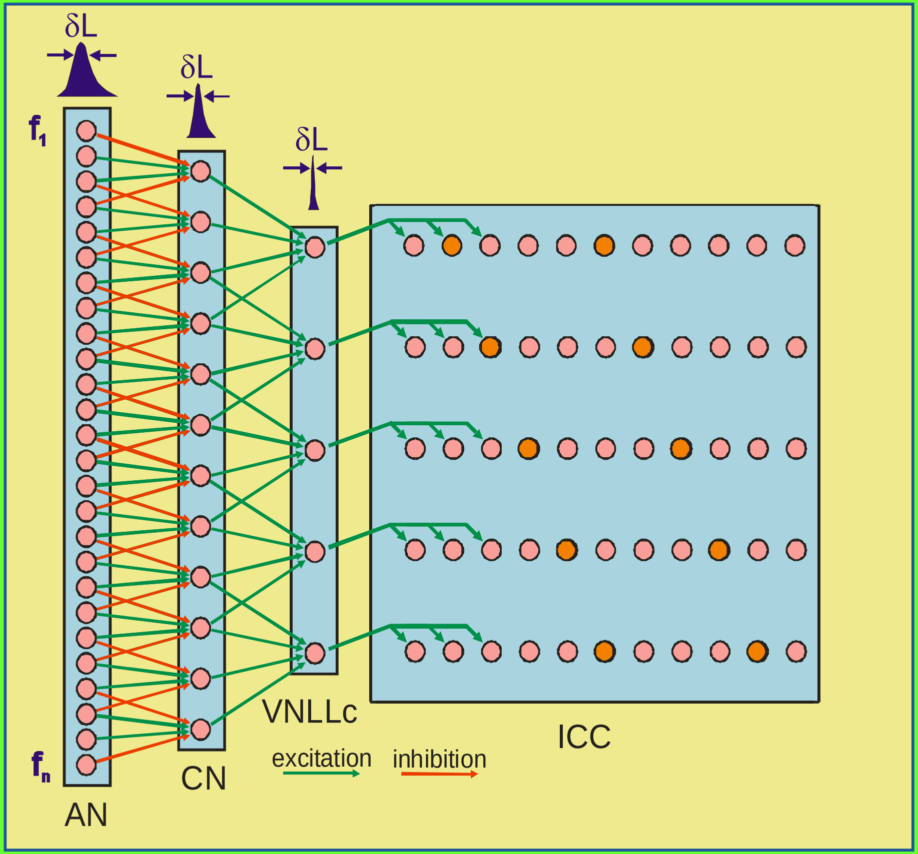


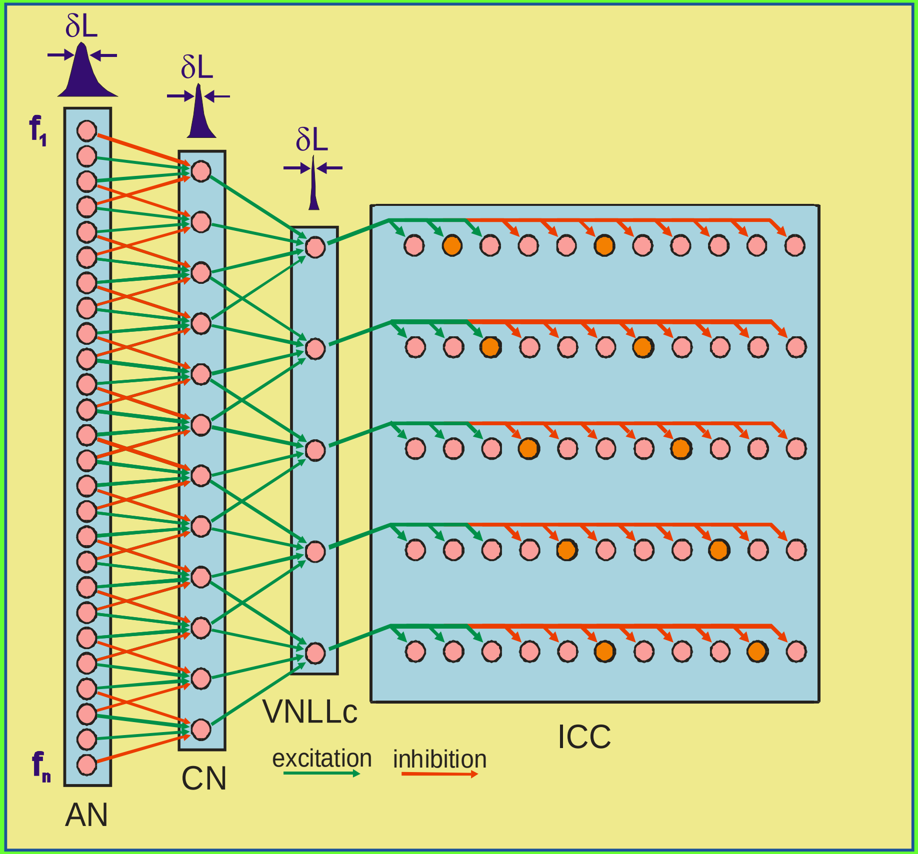
δL
δL
δL
f1
fn
AN
CN
VNLLc
ICC
excitation
inhibition

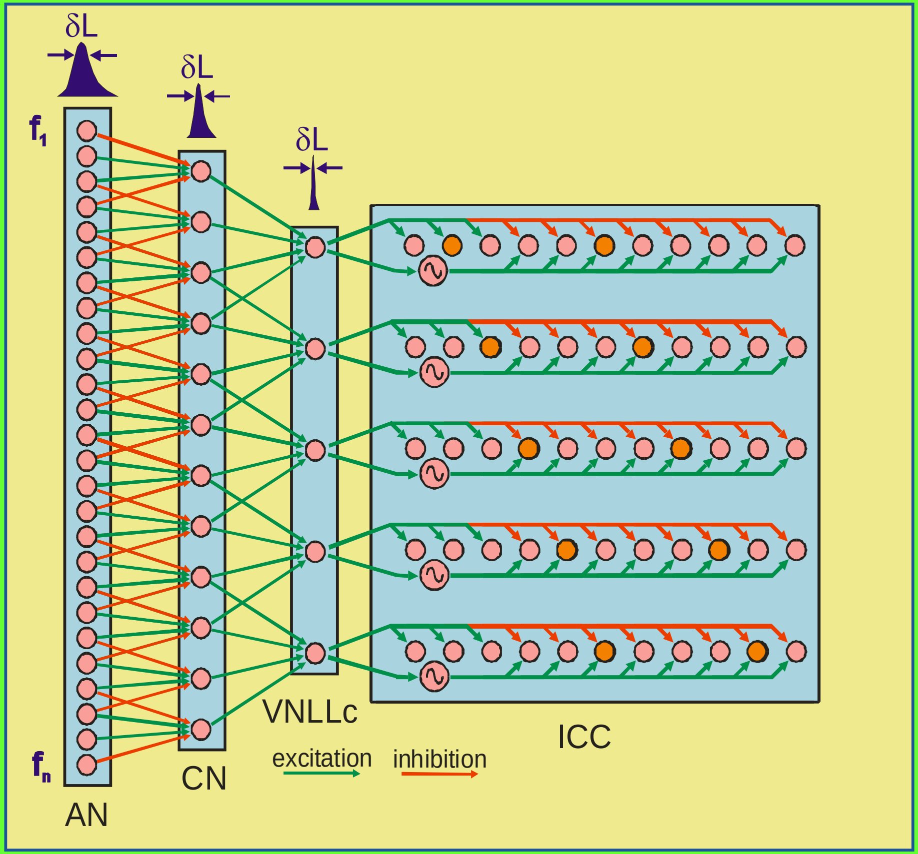

sharpness of tuning
Q (fc/Δf)
100
80
60
40
20
10
8
6
4
2
1
10
20
30
40
60
80
100
fc (kHz)



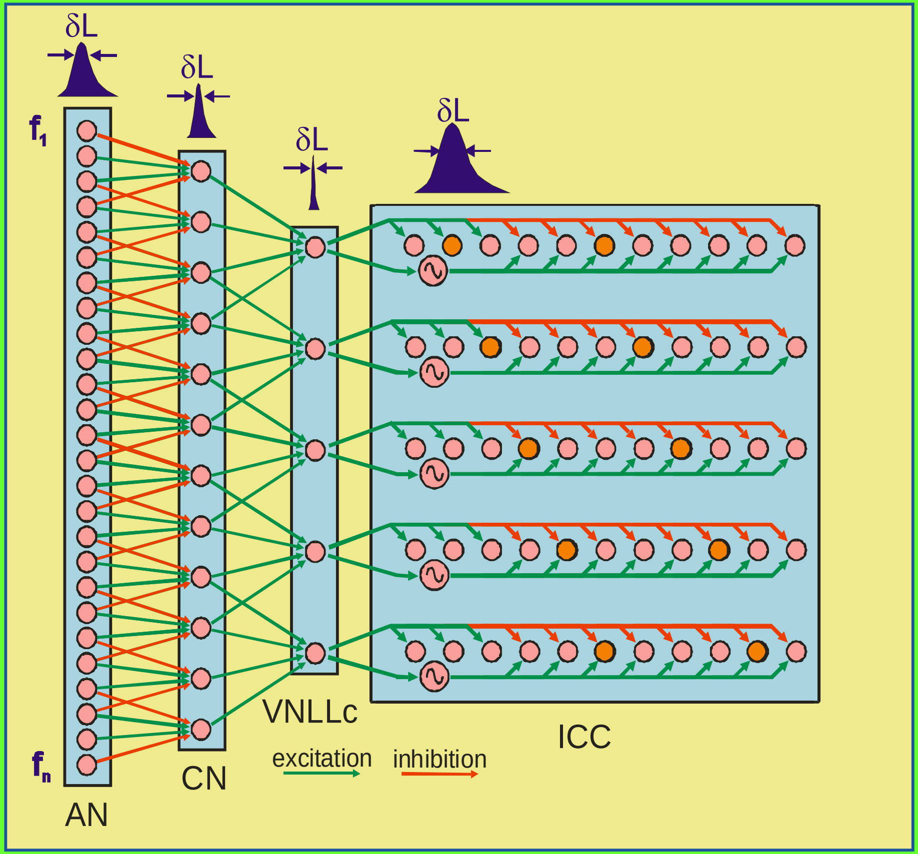
δL
δL
δL
f1
fn
AN
CN
VNLLc
ICC
excitation
inhibition

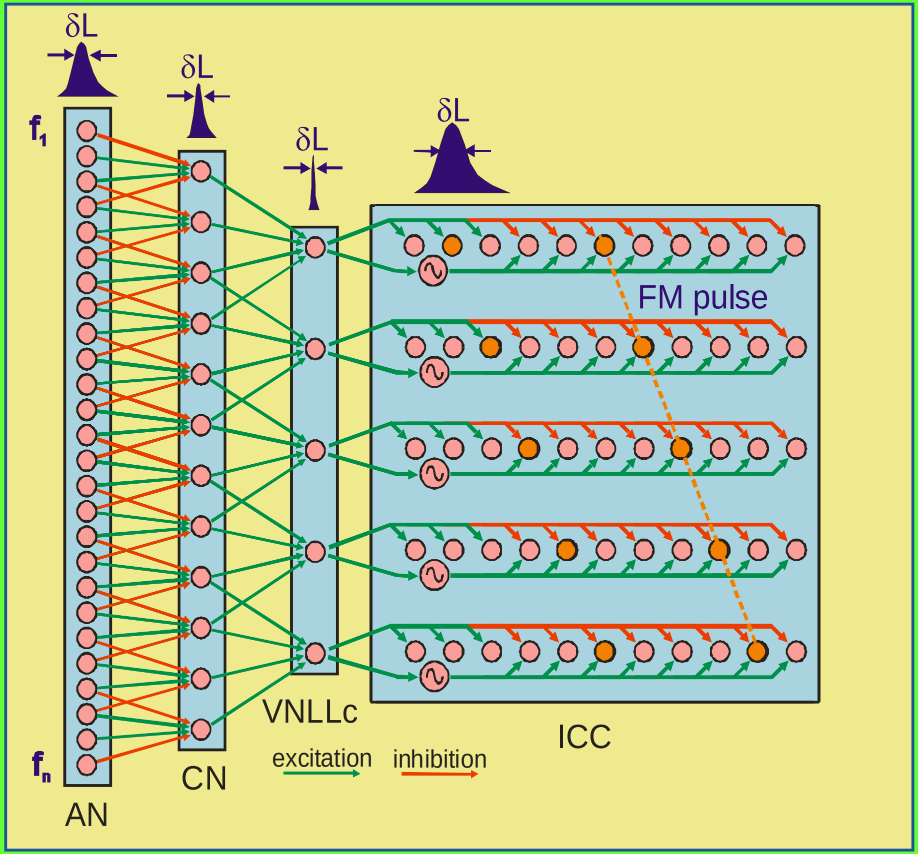

δL
δL
δL
f1
fn
AN
CN
VNLLc
ICC
excitation
inhibition

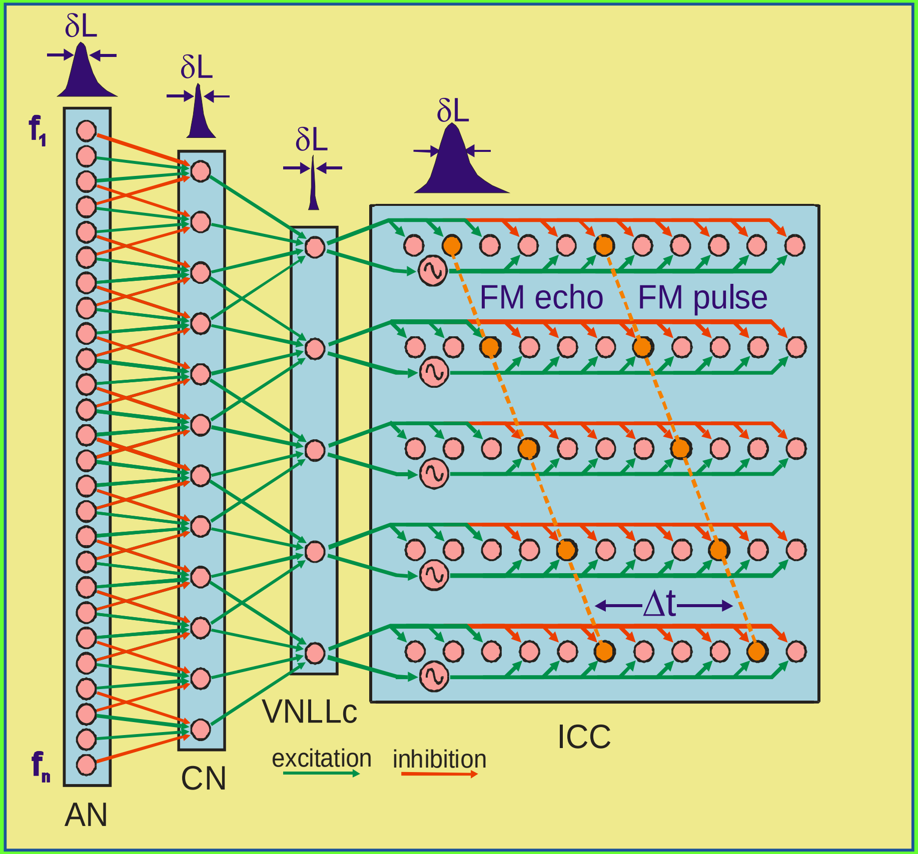

δL
δL
δL
f1
fn
AN
CN
VNLLc
ICC
excitation
inhibition



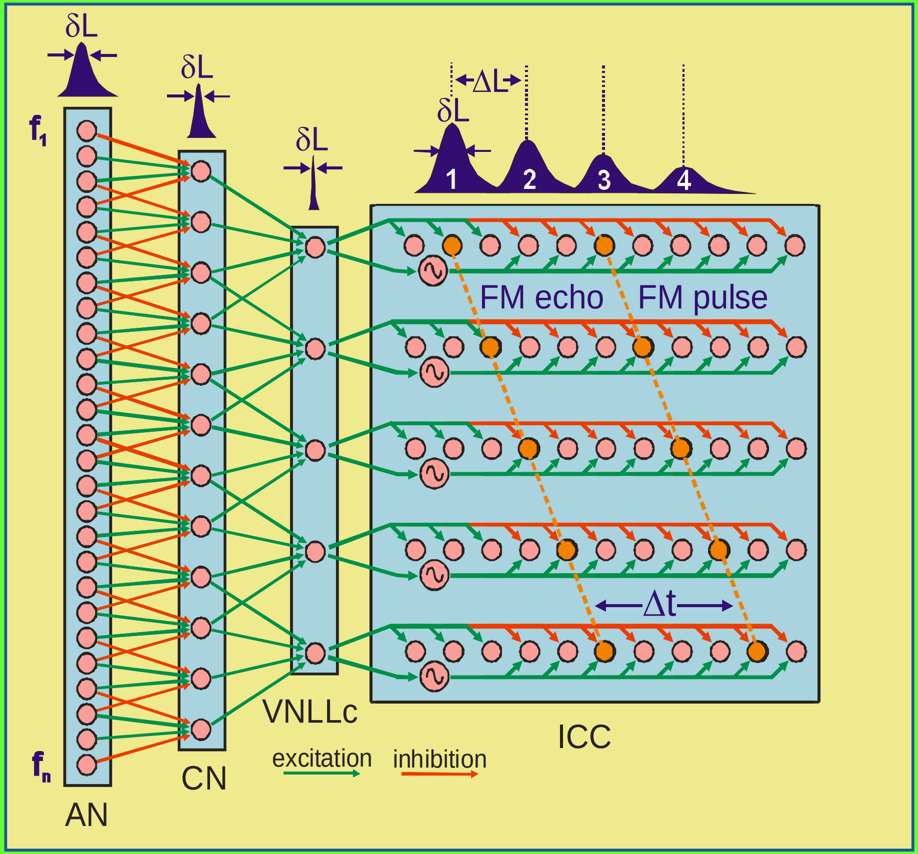
δL
δL
δL
f1
fn
AN
CN
VNLLc
ICC
excitation
inhibition

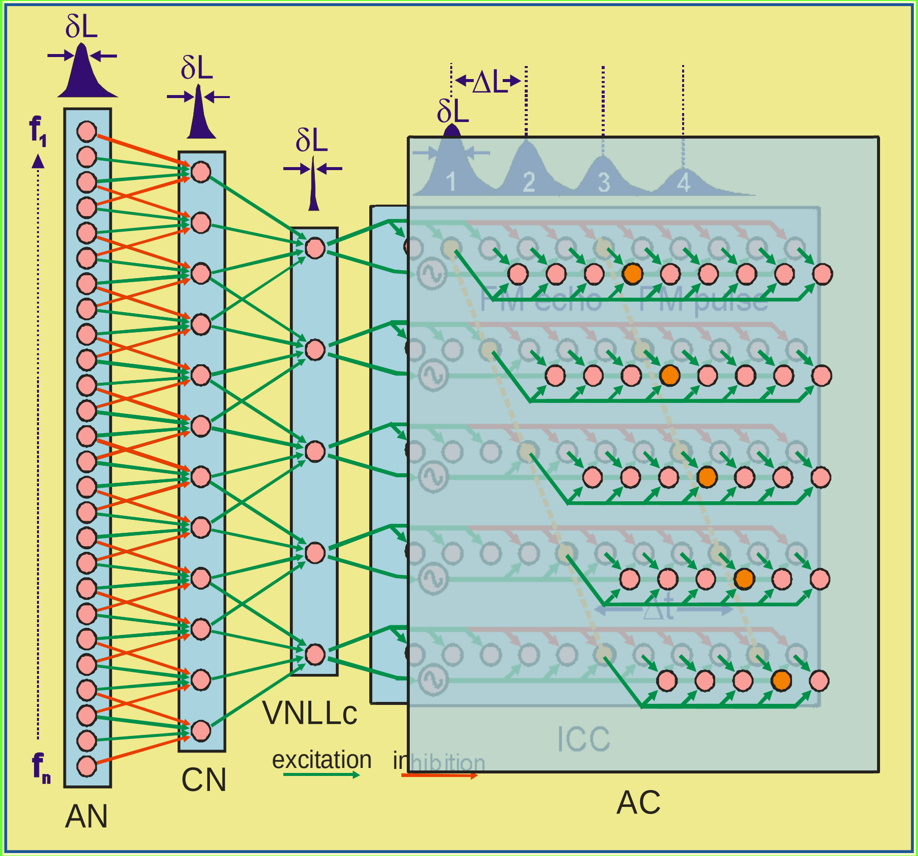

δL
δL
δL
δL
f1
fn
AN
CN
VNLLc
ICC
excitation
inhibition

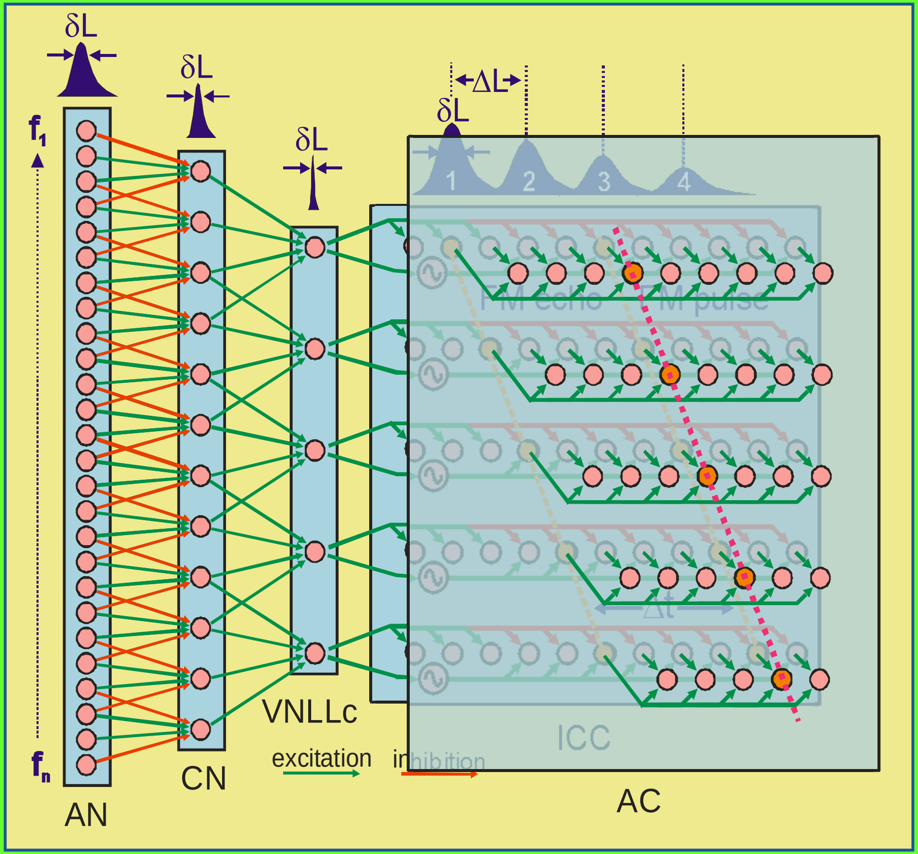

δL
δL
δL
δL
f1
fn
FM pulse
AN
CN
VNLLc
ICC
excitation
inhibition

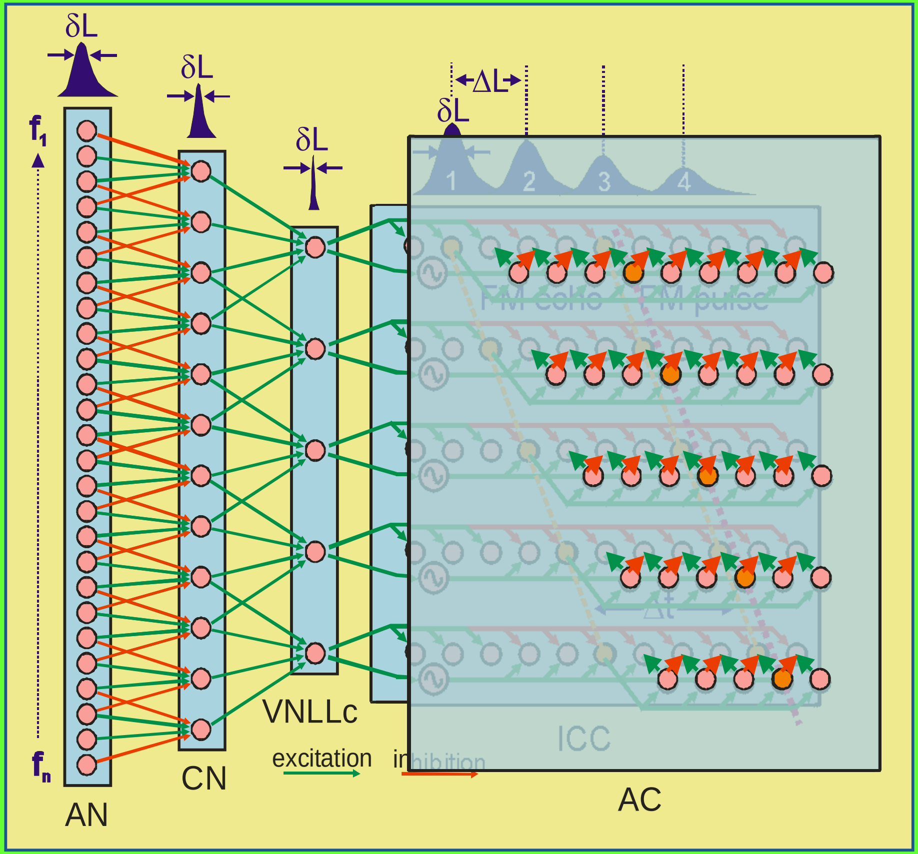


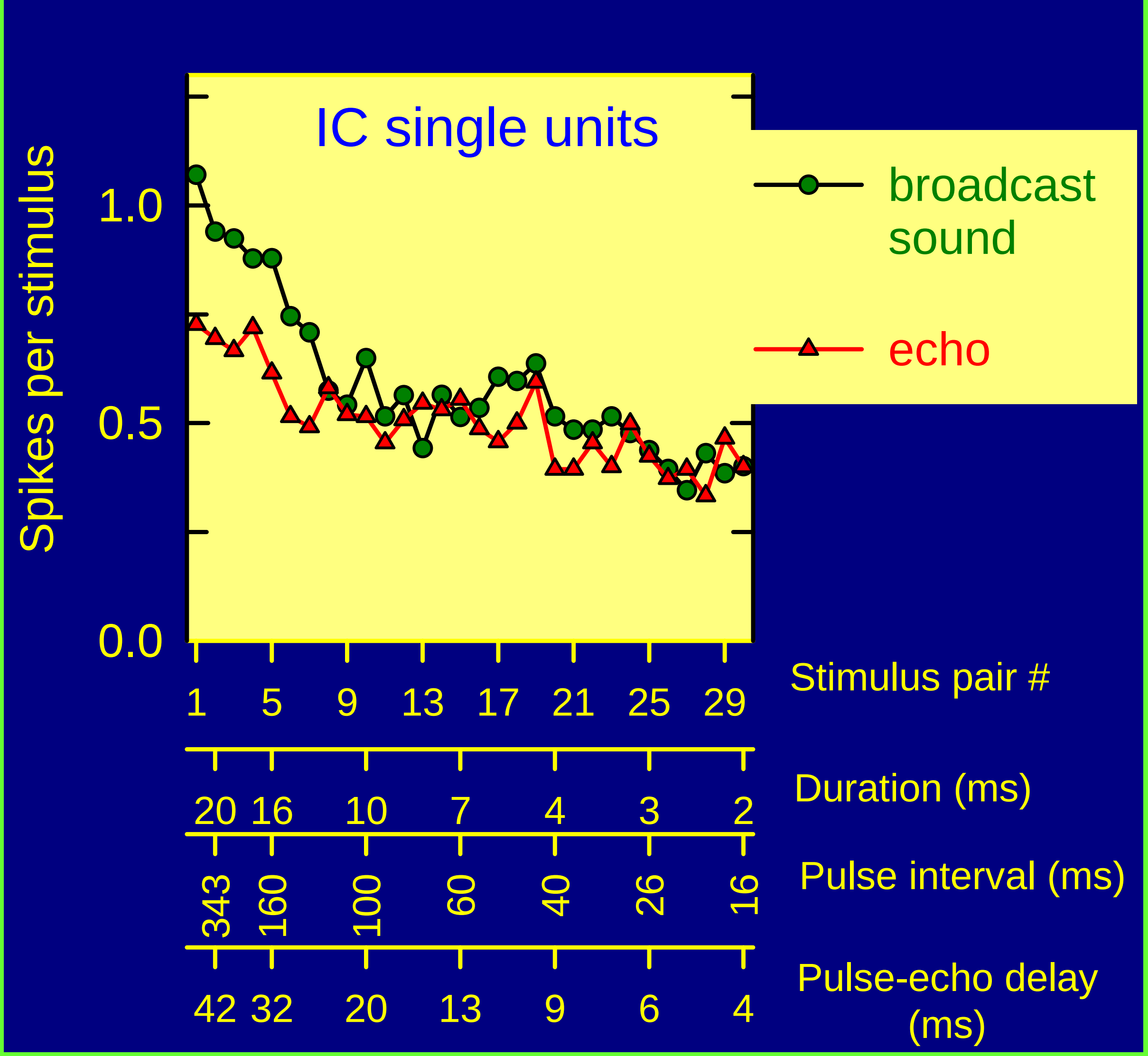
δL
δL
δL
δL
f1
fn
FM echo
FM pulse
Δt
AN
CN
VNLLc
ICC
excitation
inhibition


δL
δL
δL
ΔL
δL
1
2
3
4
f1
fn
AN
CN
VNLLc
ICC
FM echo
FM pulse
Δt
excitation
inhibition

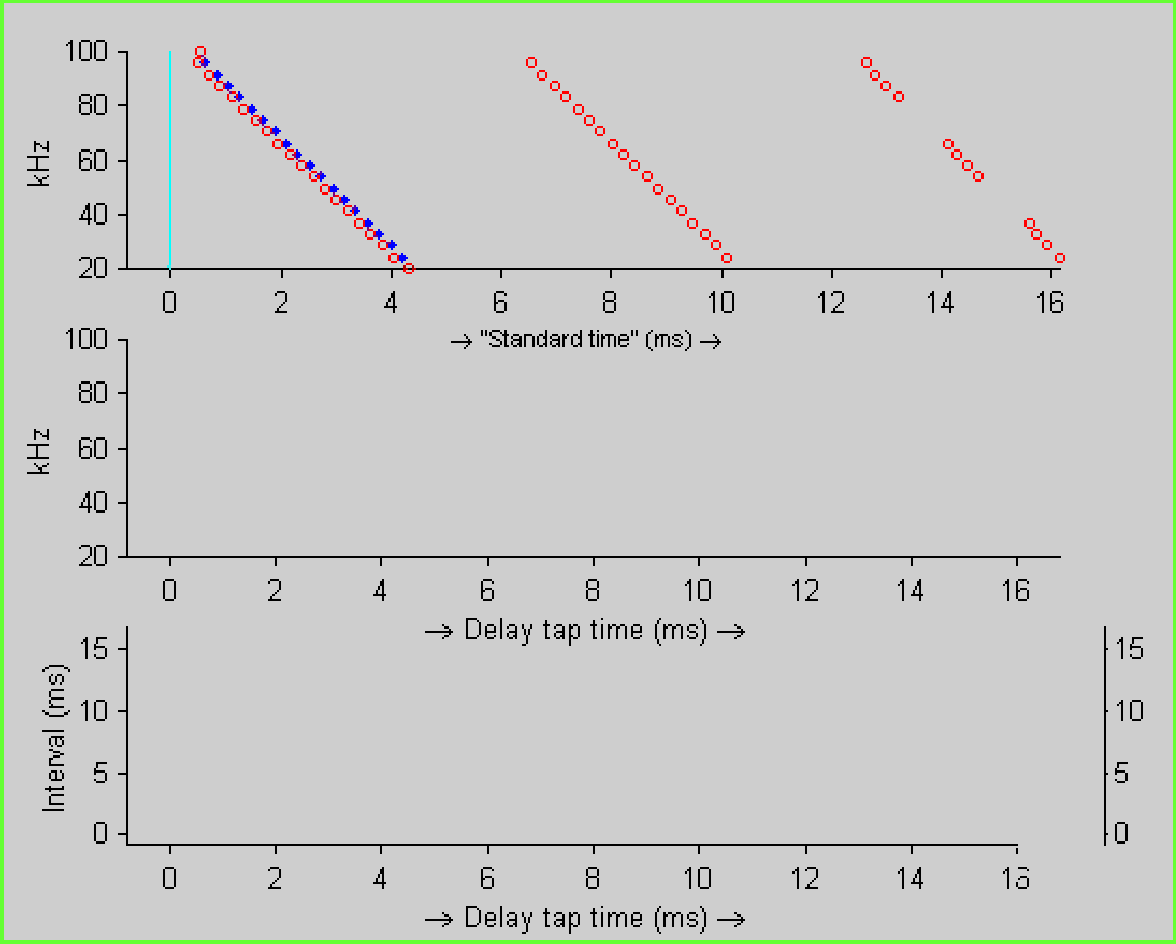

δL
δL
δL
ΔL
δL
f1
fn
1
2
3
4
FM echo
FM pulse
Δt
VNLLc
ICC
excitation
inhibition
AN
CN
AC


δL
δL
δL
ΔL
δL
1
2
3
4
f1
fn
FM echo
FM pulse
Δt
AN
CN
VNLLc
excitation
inhibition
ICC
AC


δL
δL
δL
ΔL
δL
1
2
3
4
f1
fn
AN
CN
VNLLc
excitation
inhibition
FM echo
FM pulse
Δt
ICC
AC

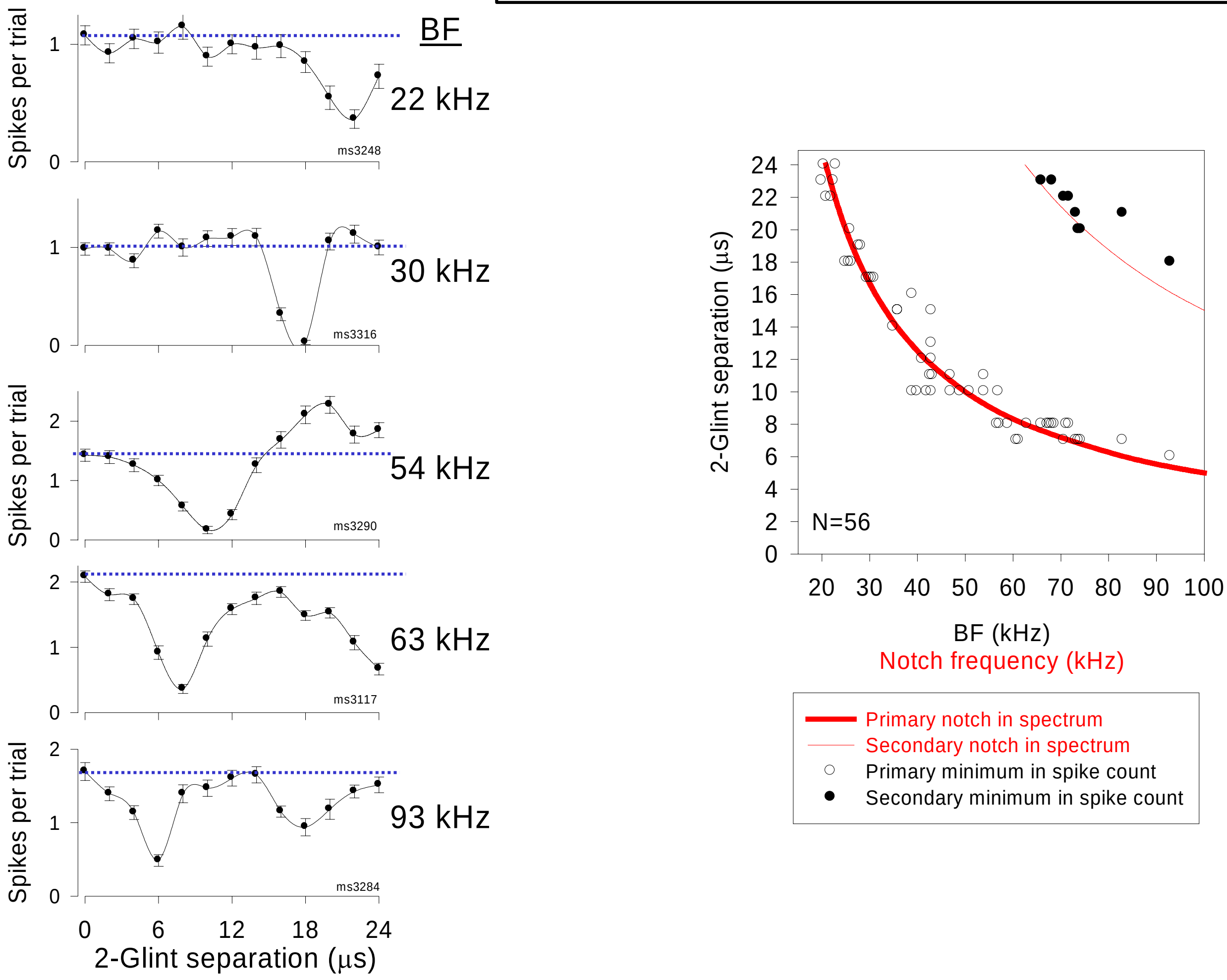


When neurons in the IC respond to their BFs in FM sweeps, they produce a single spike to register the time-of-occurrence of that frequency. Stronger sounds do not evoke multiple spikes, so each neuron encodes only instantaneous frequency around BF.

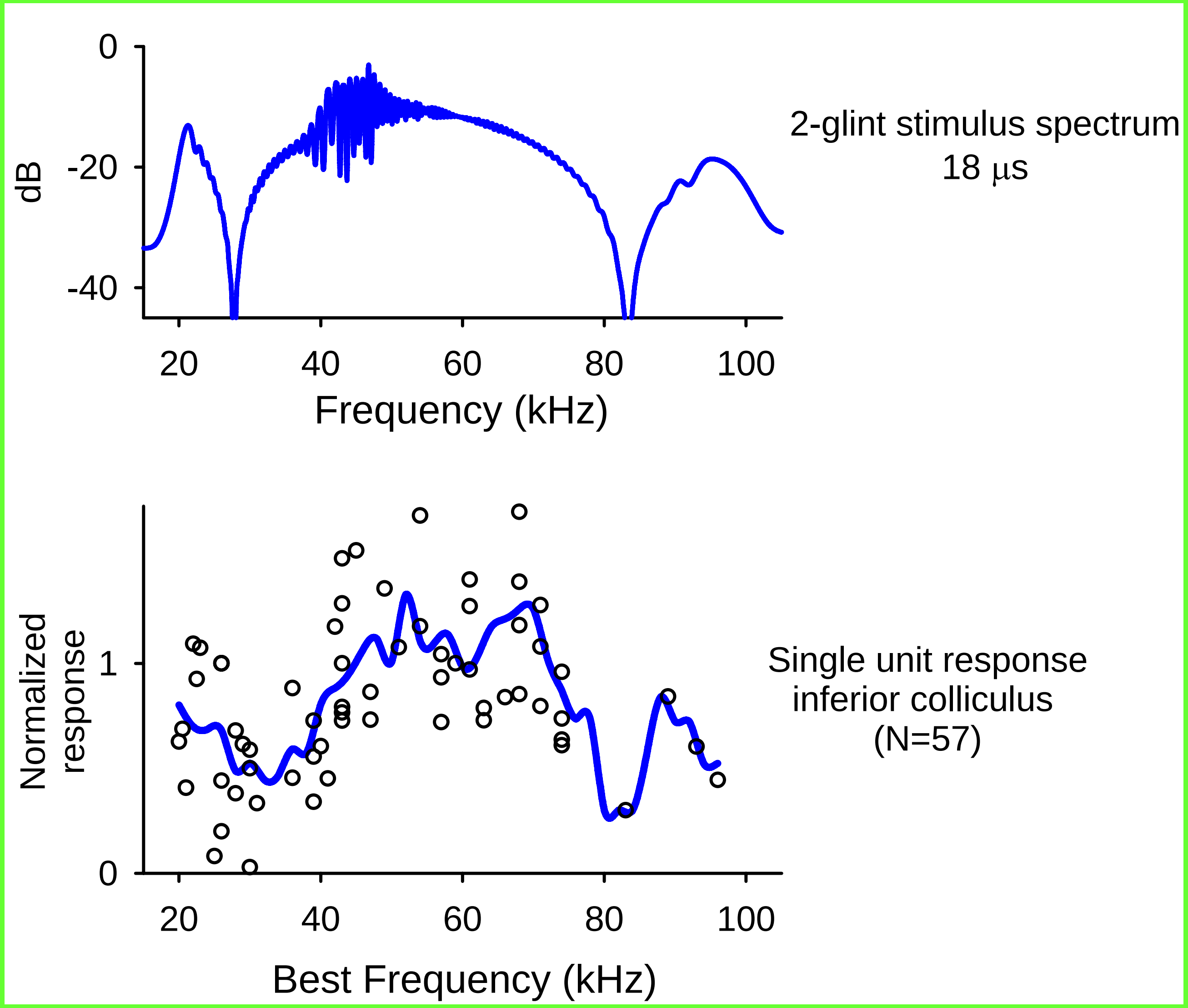


The best way to illustrate the temporal organization of the bat's cascade of representations is with animation of an auditory model. In this example, the broadcast sweep is 4 ms long, and there are echoes at delays of 6 ms and 12 ms. The IC delay-lines store the sweeps for display by delay-tuned neurons in the AC.

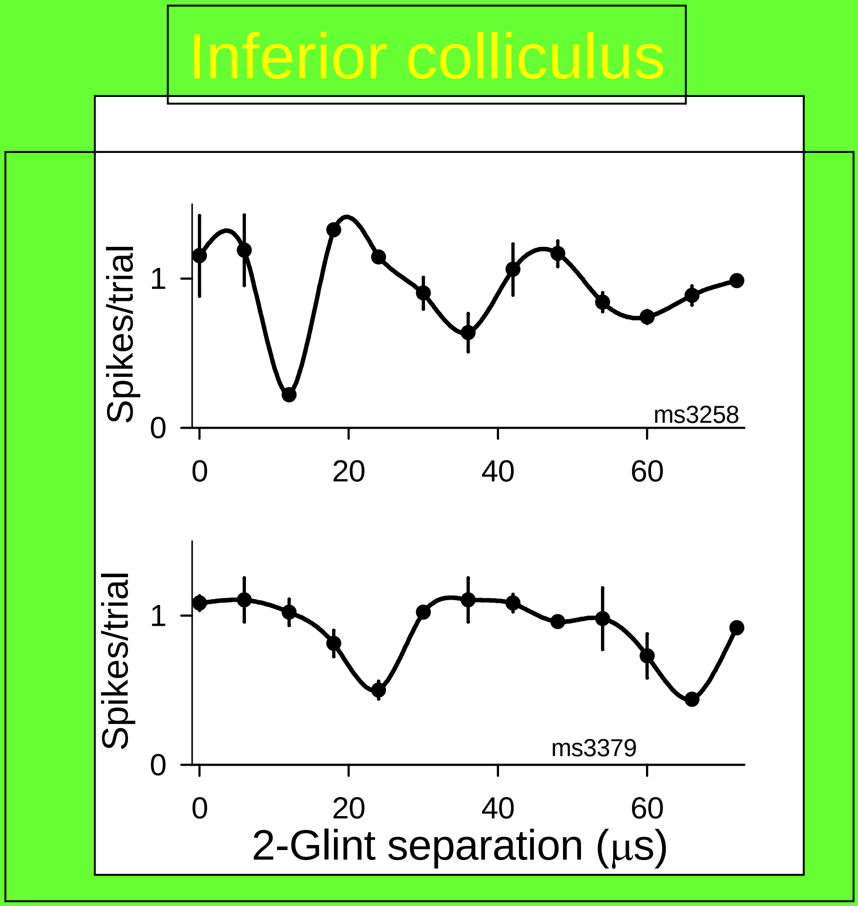
IC single units: overlapping FM sweeps

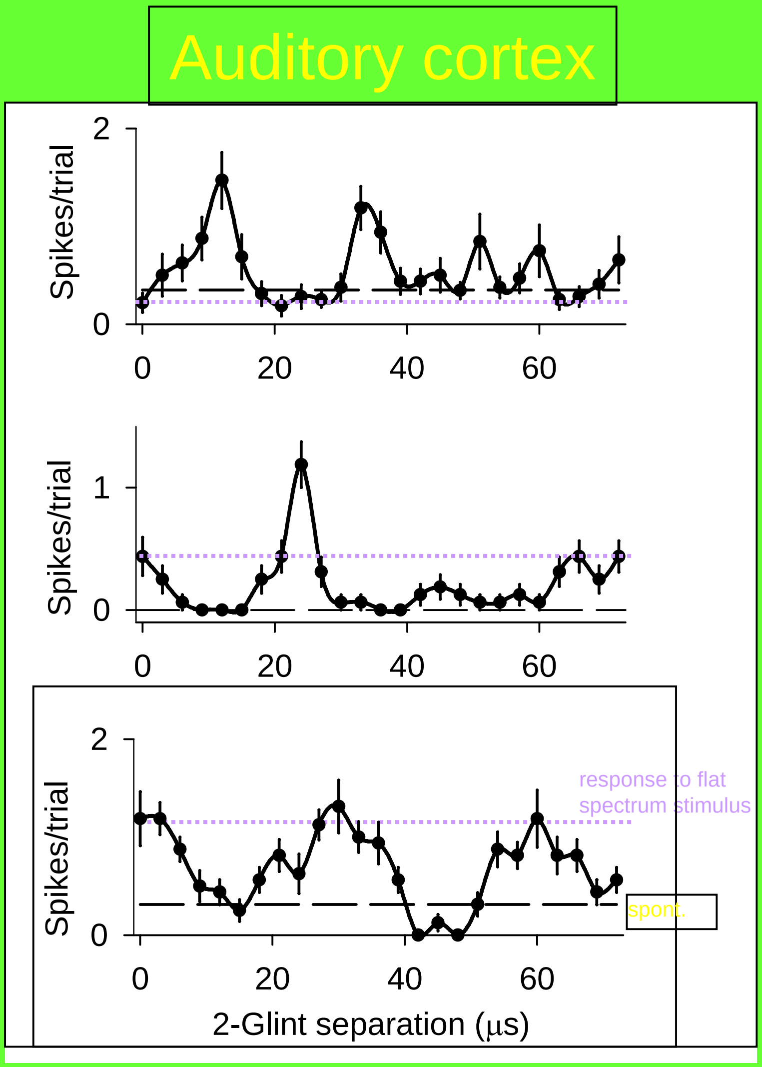


Combining registration of instantaneous frequency with the effects of inhibition, IC neurons encode the presence of interference notches around BF, too.

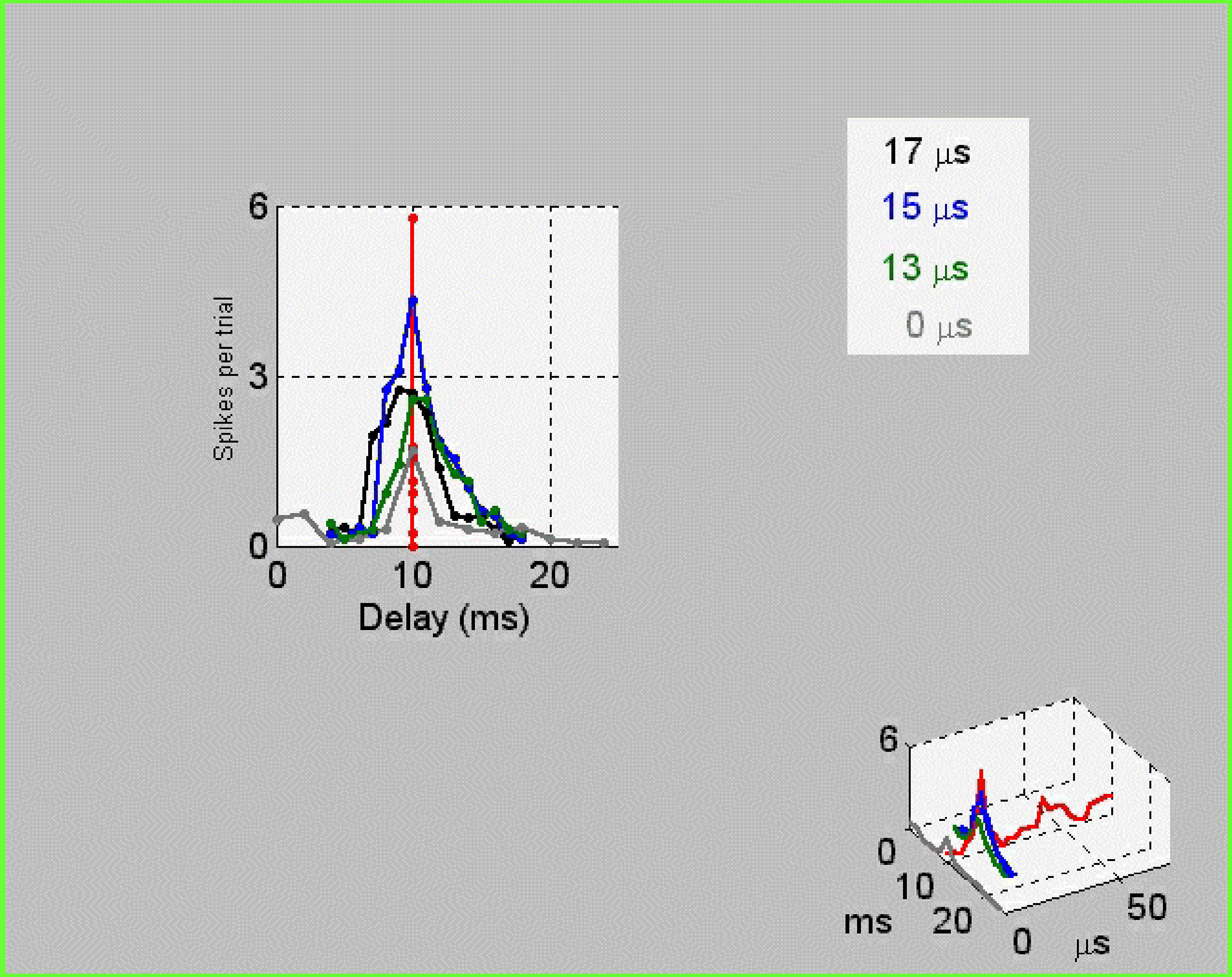


Across a population of IC neurons tuned to different BFs, the shape of the spectrum is encoded by the probability of occurrence of single spikes.





Whereas IC neurons respond to notches by *not* responding at notch frequency, AC neurons respond by spiking to the *presence* of the notch.



By spiking only to the notches, cortical neurons represent the timing of second and higher glints from the interference spectrum.

Appendix 3d

Pat Moore

Science, Technical Innovation and Applications in Bioacoustics
A Workshop

4-5 May 2004
North Berwick, Scotland
2004

"Overview of Dolphin Biosonar"

Patrick W. Moore

Head, Biosonar Program Office, Code 23502

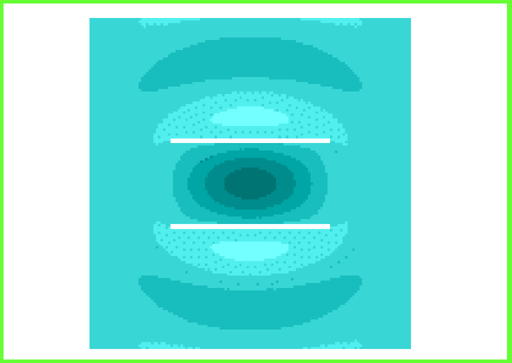
Head, Scientific and Veterinary support Branch, Code 2351

Space and Naval Warfare Systems Center (SSC-SD)

San Diego, California

Performance

- **Radar & Sonar systems rely on and are limited by standard physical properties**
  - **Power transmitted (source Level)**
  - **Power reflected by target (Target Strength)**
  - **The signal attenuation of the media between transmitter and receiver (transmission Loss)**
  - **The background noise level (ambient noise)**
  - **Receiver performance (DI)**



For active noise-limited monostatic sonar performance the equation may be written as follows:

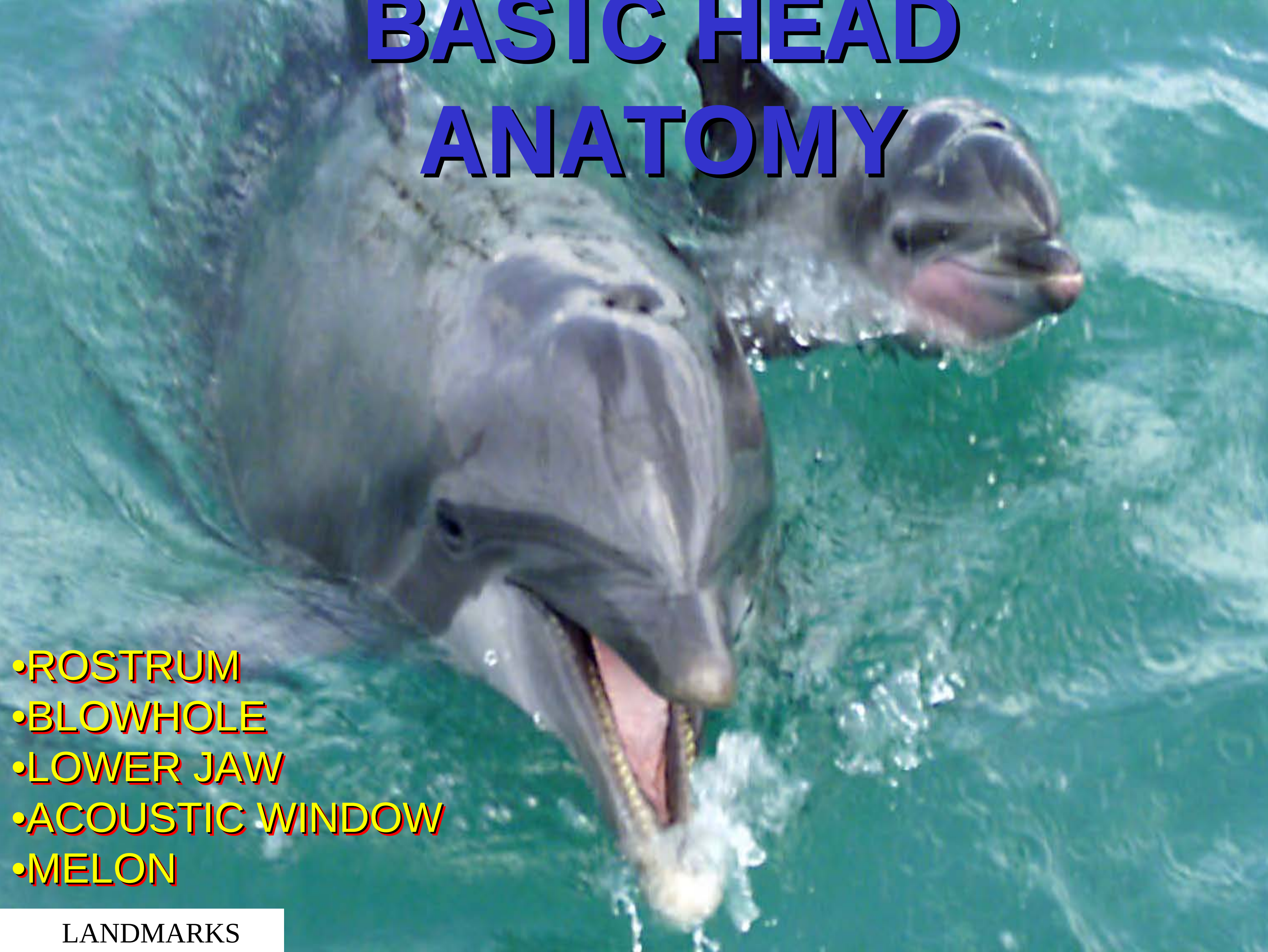
$$DT = SL - 2TL + TS - (NL - DI)$$

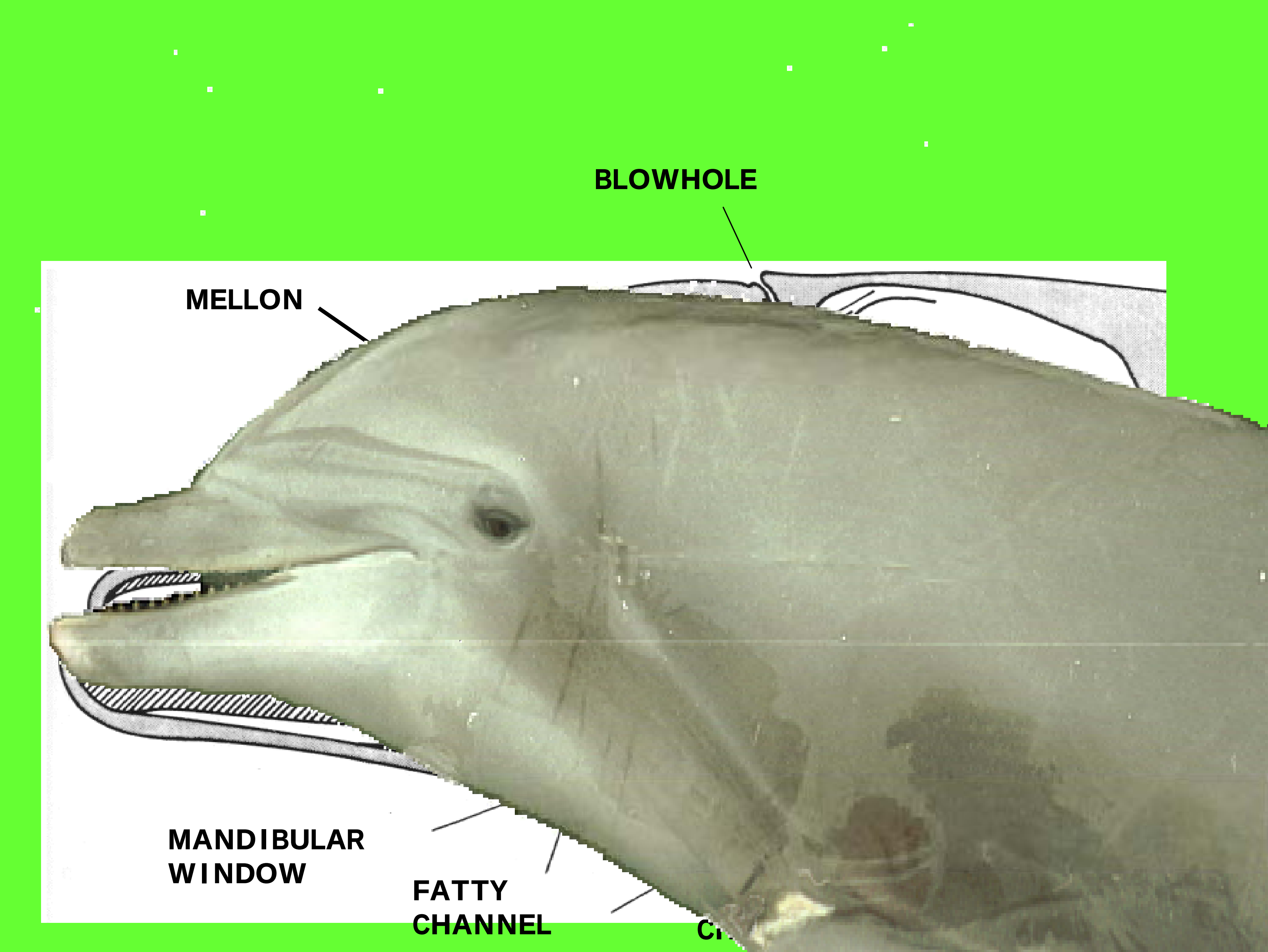
DT = Detection Threshold
SL = Source Level

BIOLOGICALLY DETERMINED

2TL = Two-way Transmission Loss
TS = Target Strength
NL = Noise Level
DI = Directivity Index

◆ To gain insight of our dolphin Biosonar we need to attempt to measure and understand these variables.

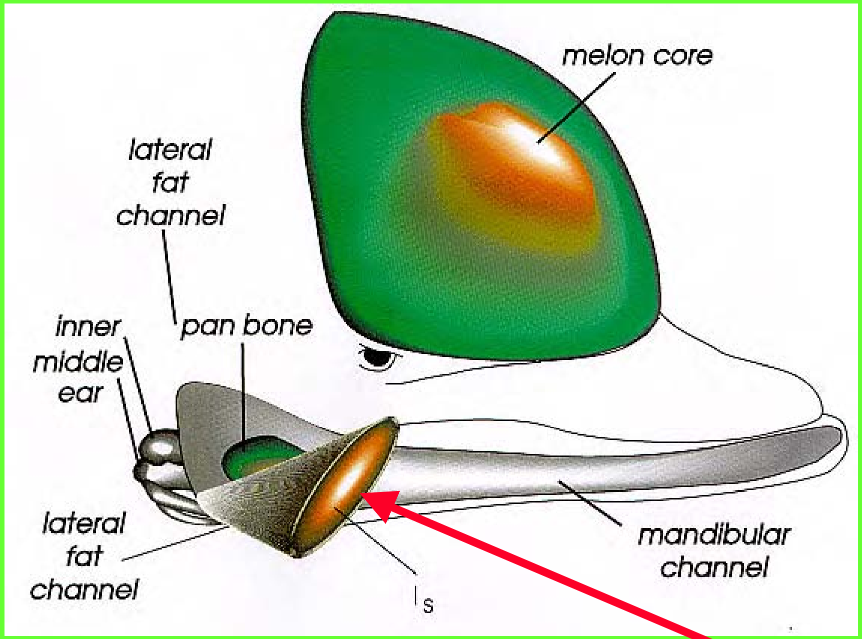

BASIC HEAD ANATOMY
•ROSTRUM
•BLOWHOLE
•LOWER JAW
•ACOUSTIC WINDOW
•MELON
LANDMARKS

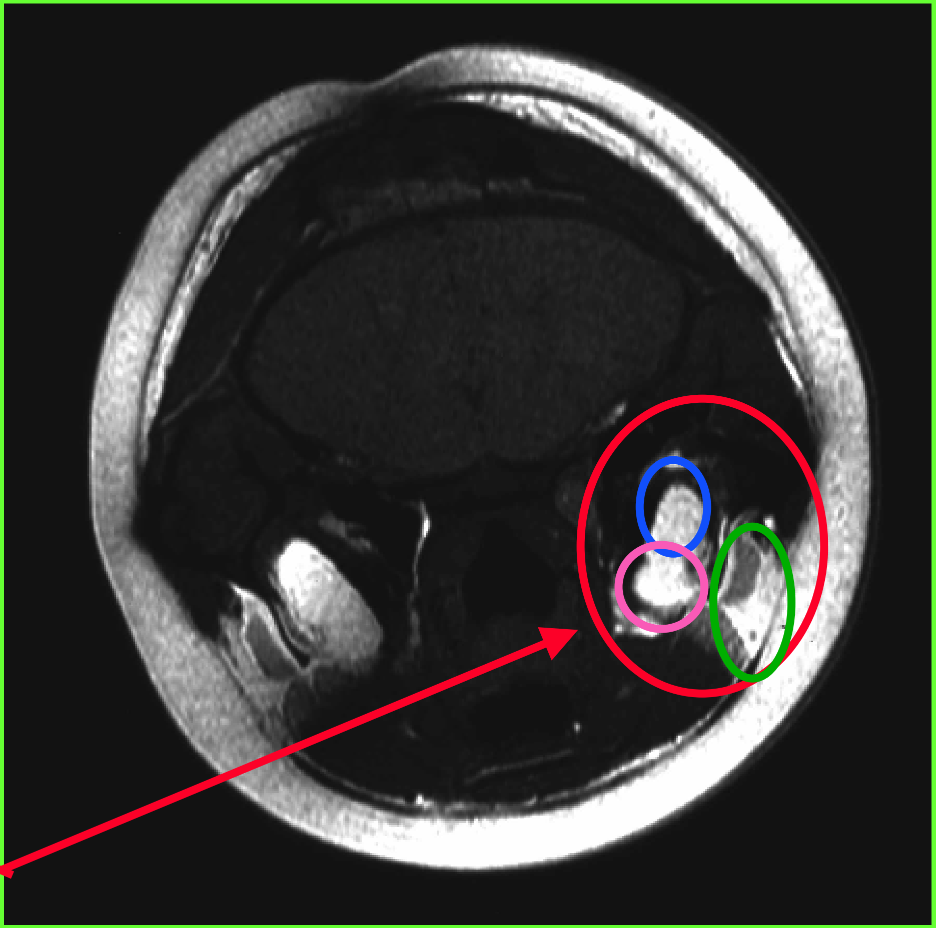

BLOWHOLE
MELLON
MANDIBULAR
WINDOW
FATTY
CHANNEL

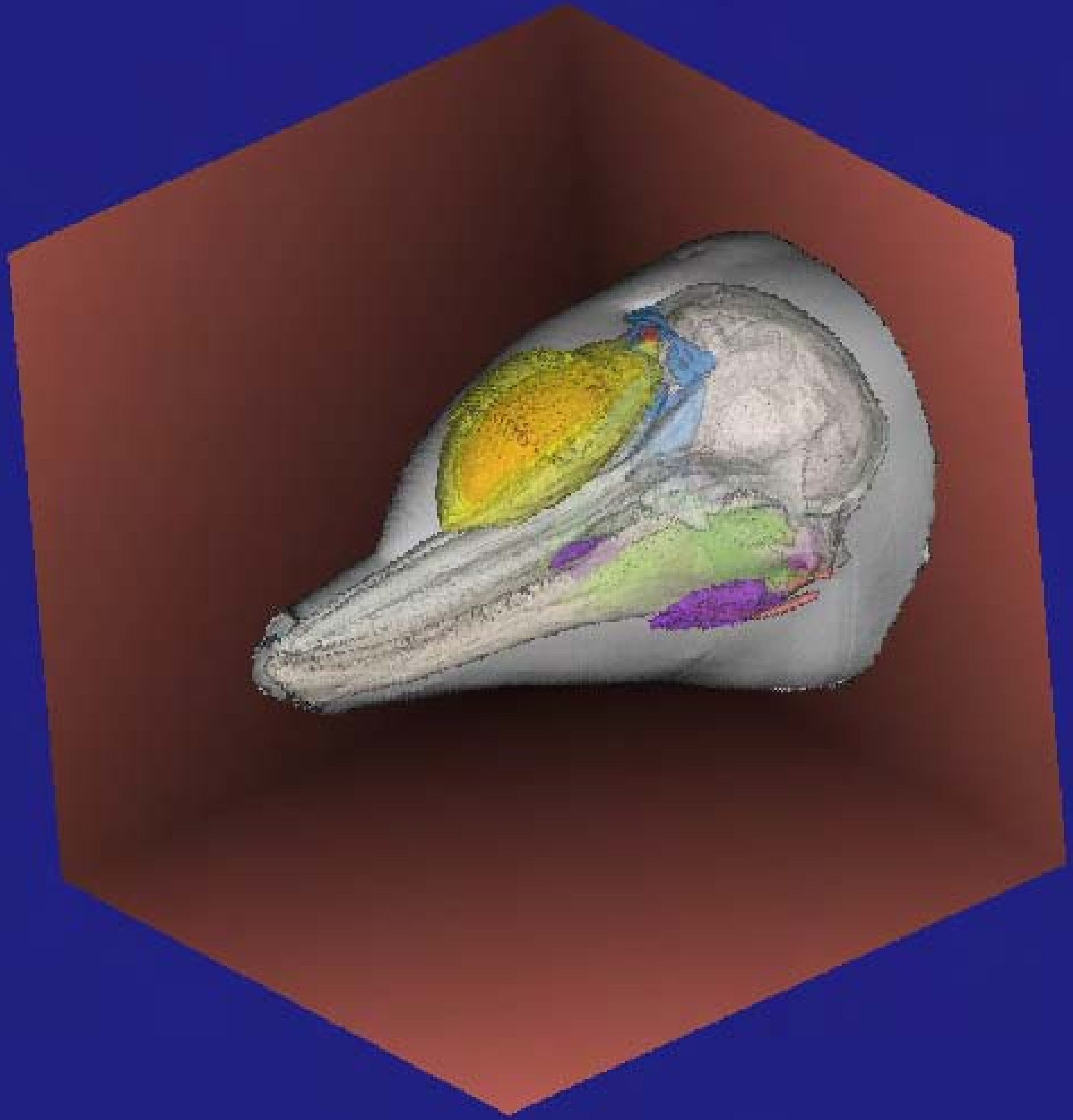
HOW DO DOLPHNS HEAR?
CURRENT CONSIDERATIONS

Discrete Bodies of "Acoustic" Fat!! (Ketten, 1994)

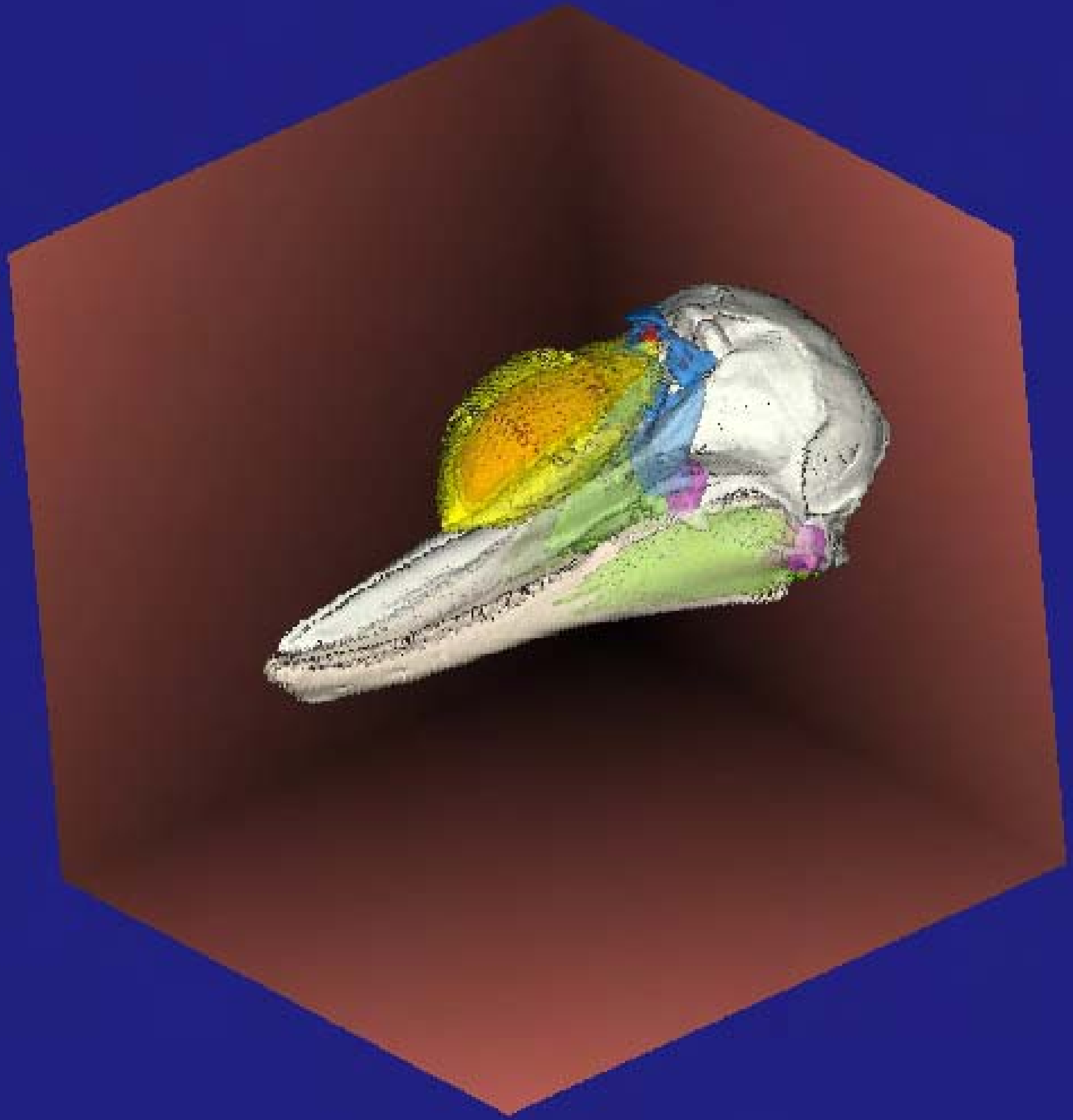
- 3 separate "channels" for high- and low-frequencies



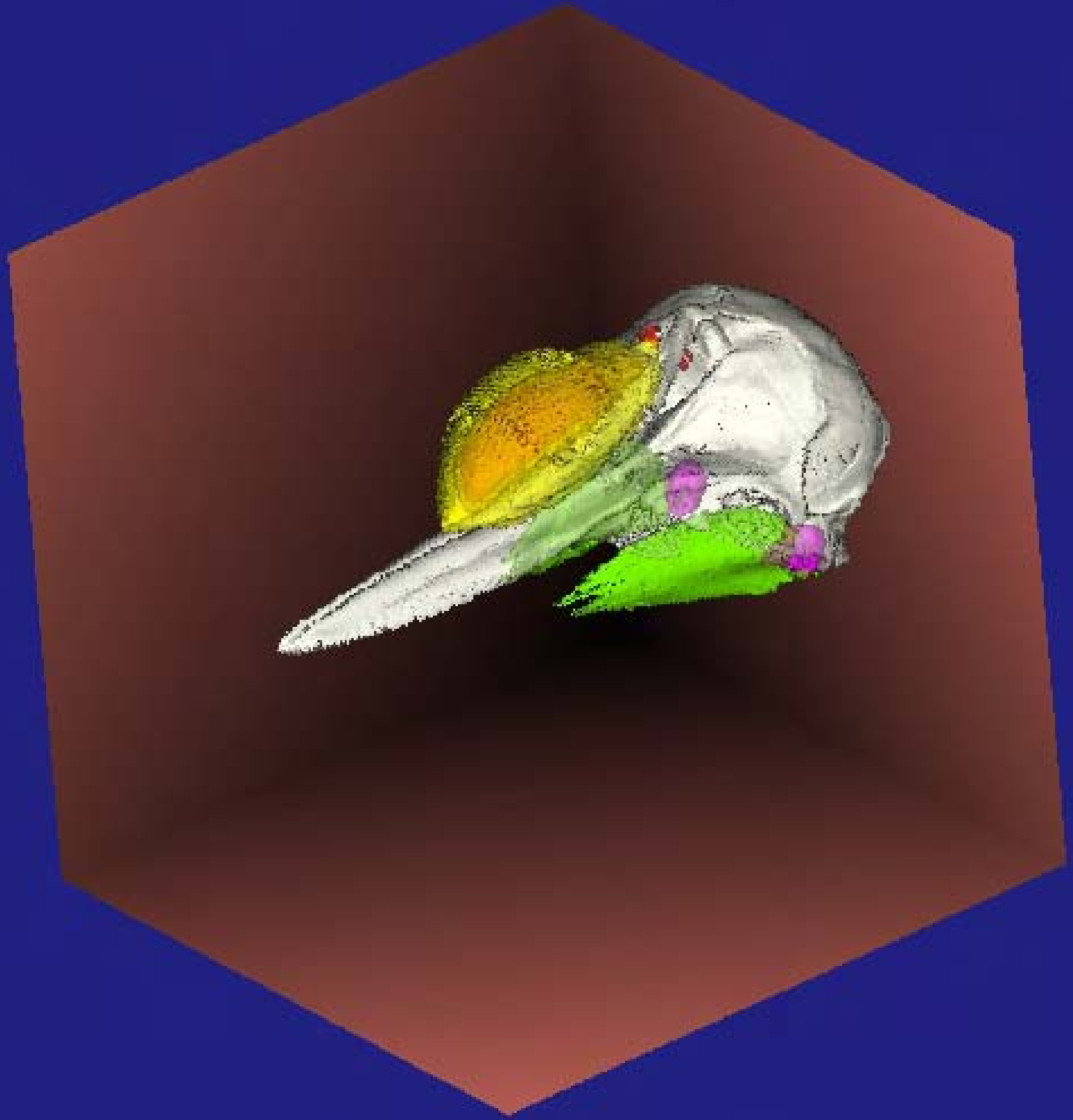




T Cranford, 2000



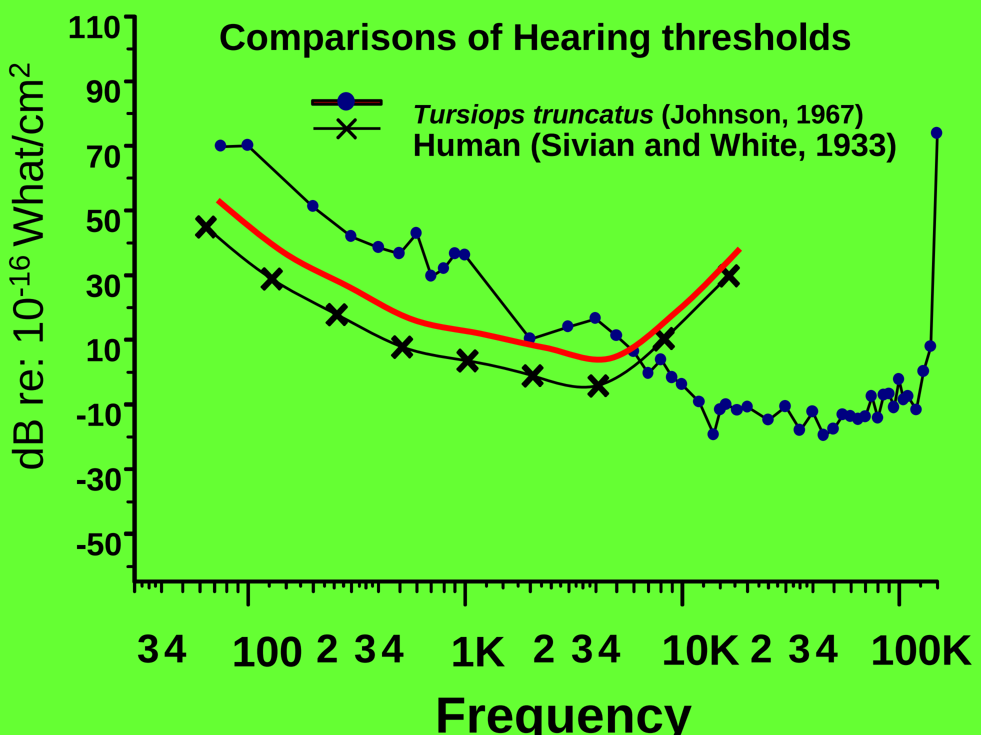
T Cranford, 2000



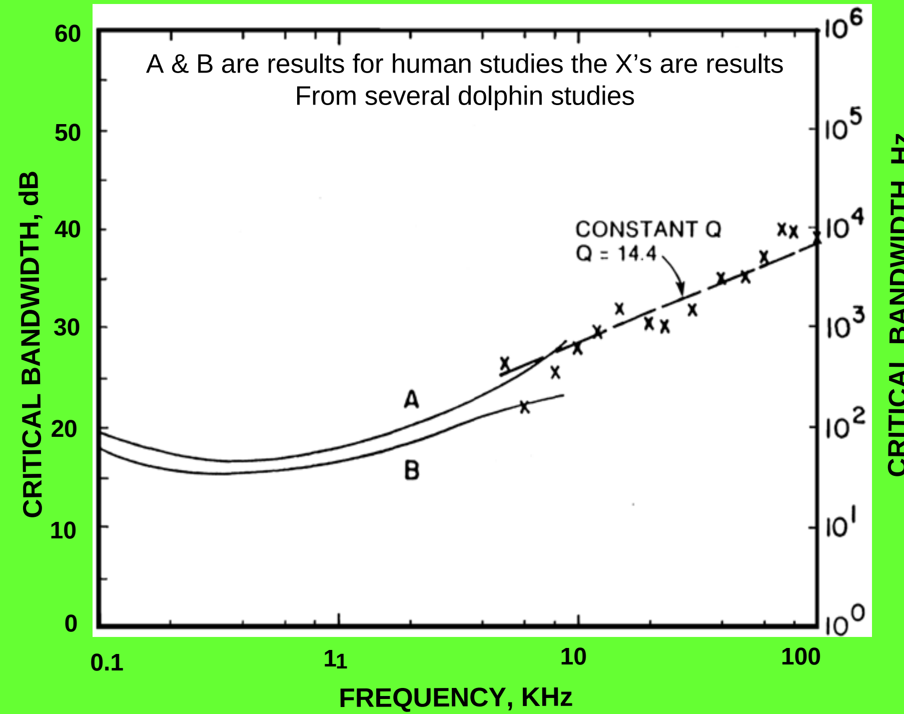
T Cranford, 2000

Dolphin Hearing

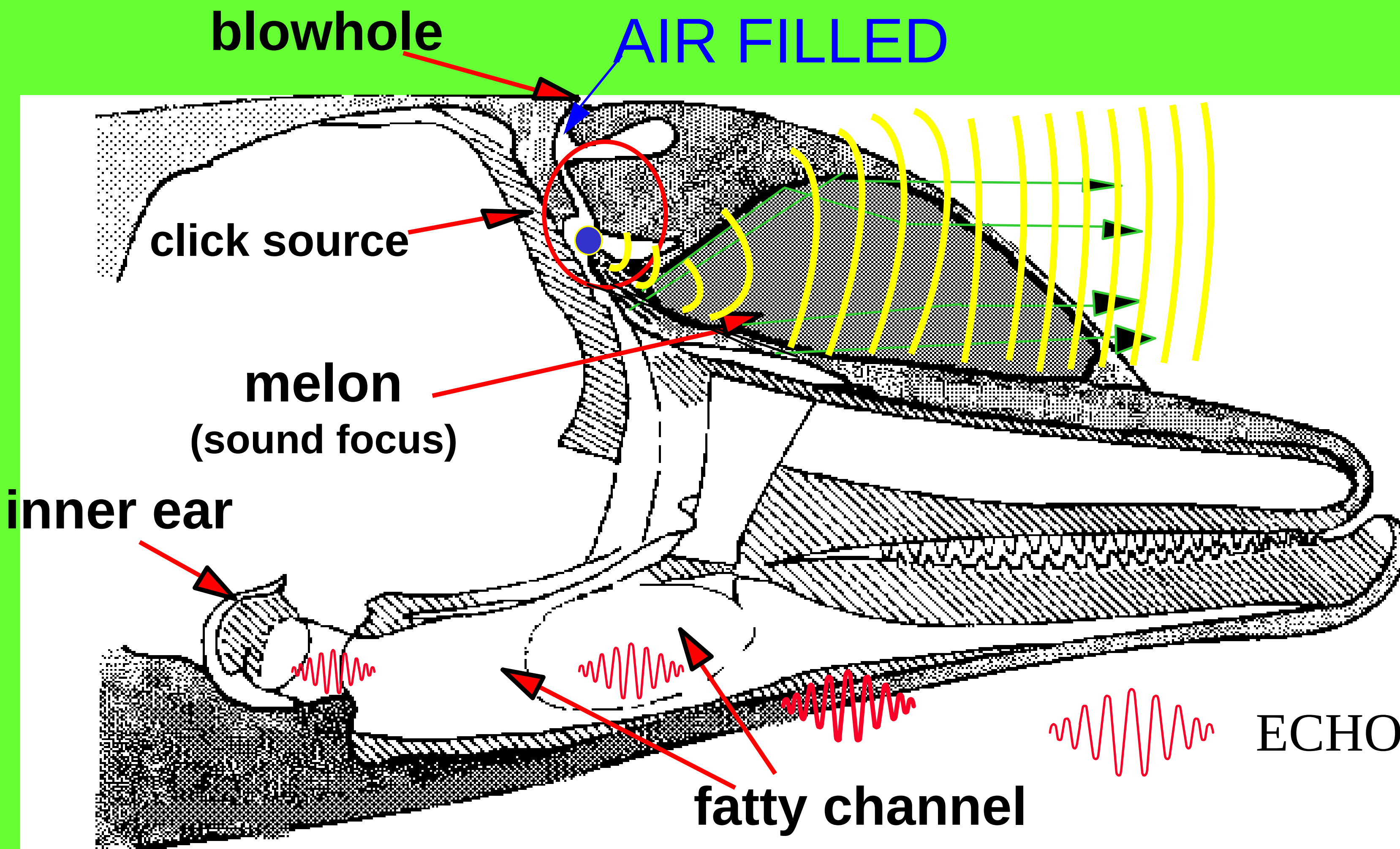
- Cochlea has basic mammalian shape - Variation in basilar membrane thickness and width is much greater
- Basilar membrane is supported by lateral structural elements
- Higher neural density



DOLPHIN AUDITORY FILTER SYSTEM

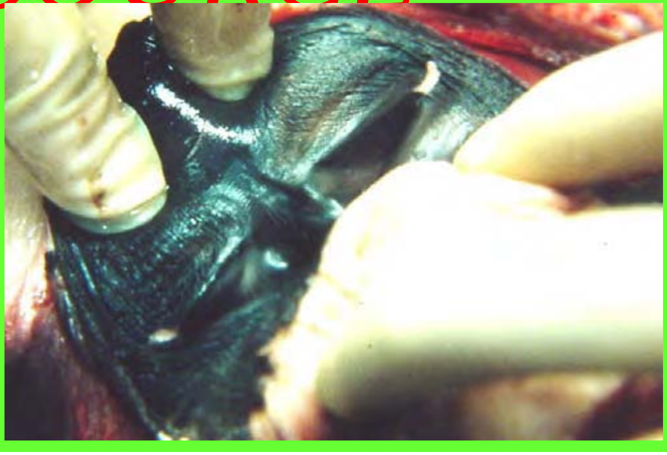


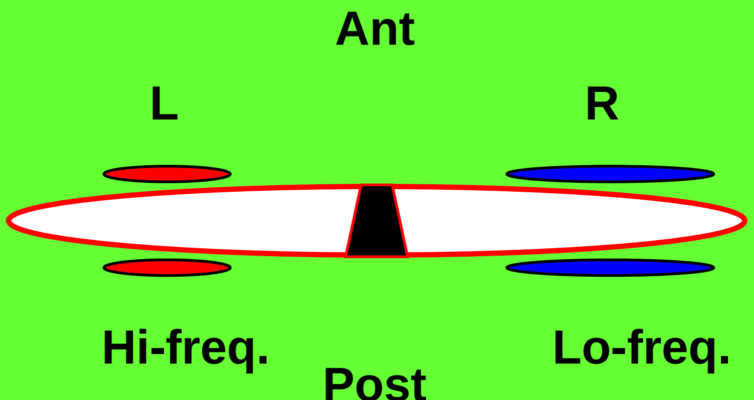
ECHOLOCATION
SIGNAL GENERATION

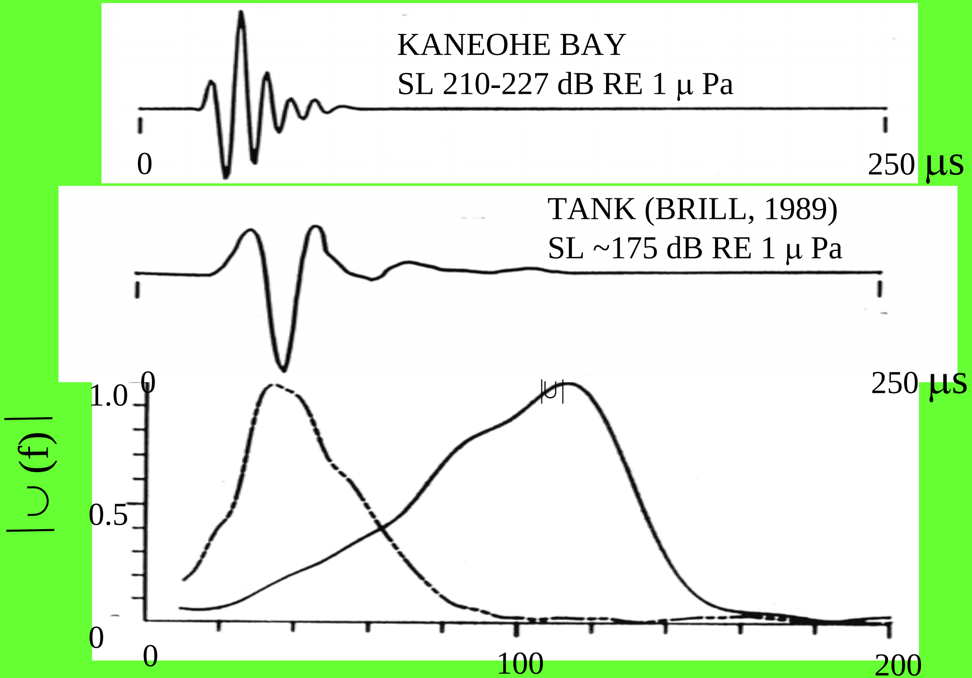


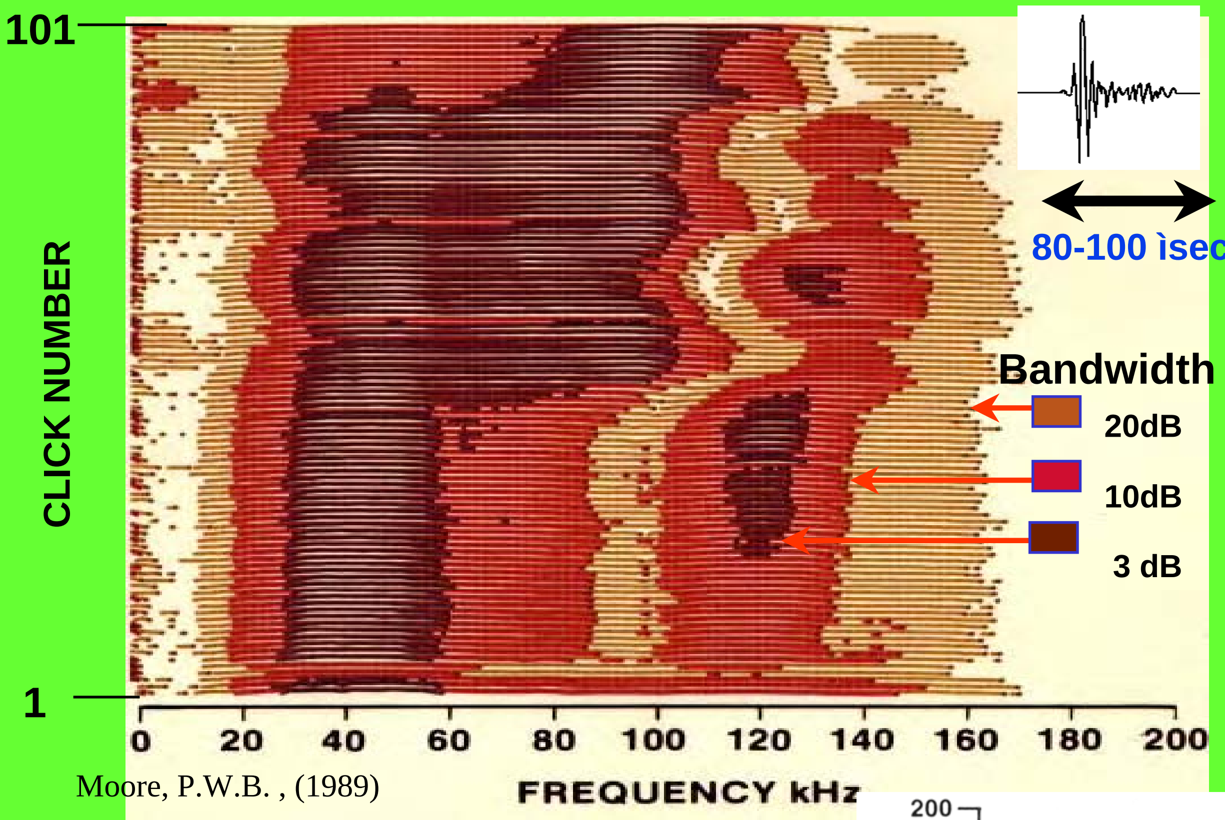
PNEUMATIC SOURCE

- **DOLPHINS & WHALES PRODUCE LOUD SIGNALS**
  - **SL's can reach 228 dB for echolocation clicks**
- **IT HAS BEEN SUGGESTED THAT DOLPHINS STUN PREY**
  - **jawclap & killer whale "bangs" - low freq. signals**
- **CAT SCAN STUDY'S CURRENTLY HAVE IDENTIFIED PROBABLE SOURCE OF SOUND**
  - **Dorsal bursae - echolocation**
  - **Entire Spiracular cavity - prey debilitation**
  - **high repetition rate**
  - **large freq. range**

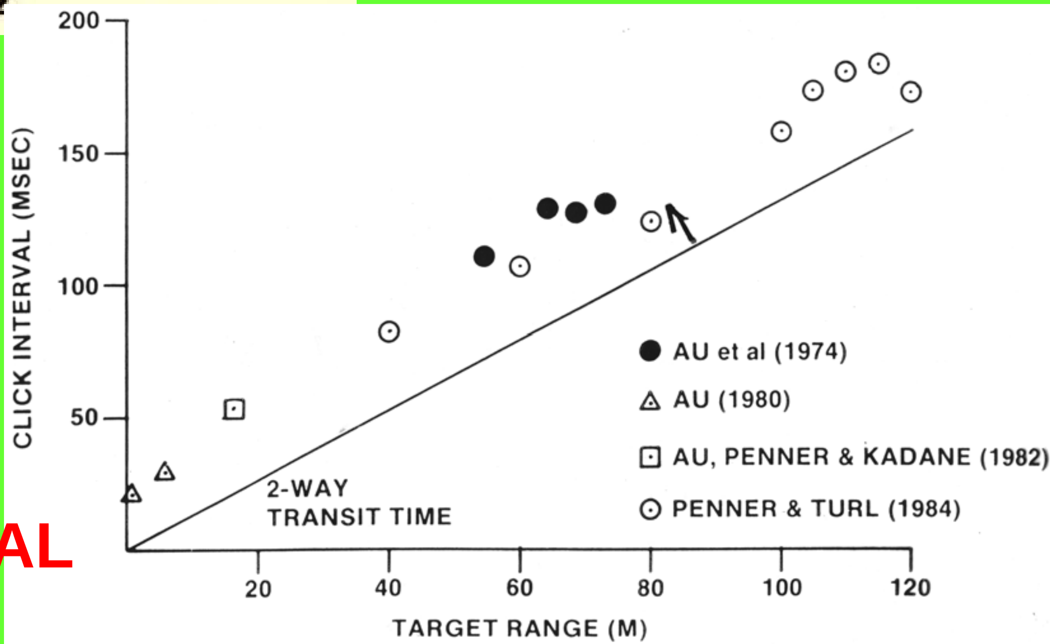








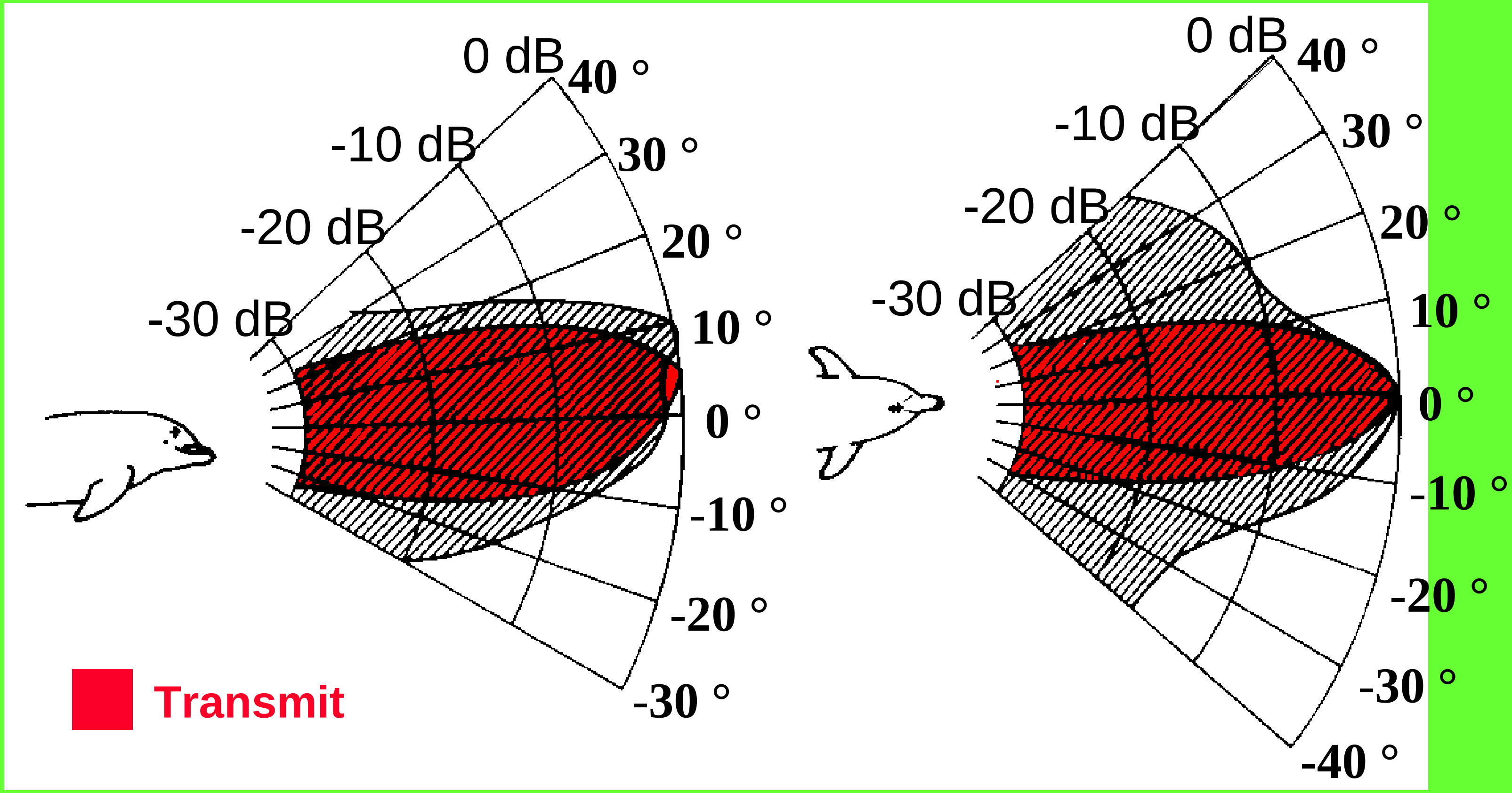
Voluntary control of adaptive signal



Emission Strategies

INTER-CLICK INTERVAL

Receive and Transmit Beams

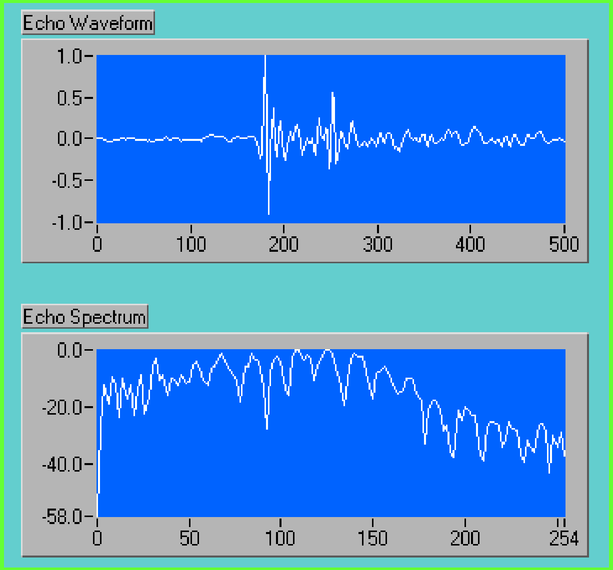


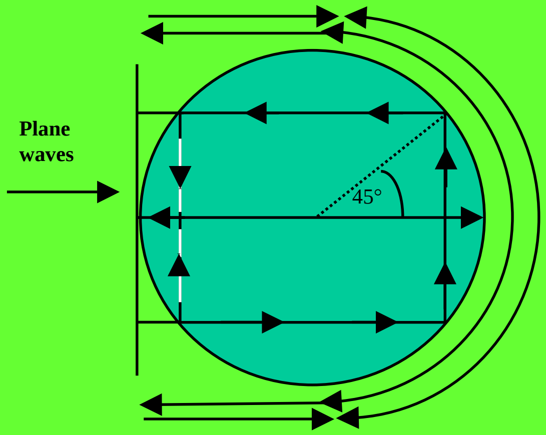
Au, W.W.L. and P.W.B. Moore, 1984

Targets Produce Complex Returns

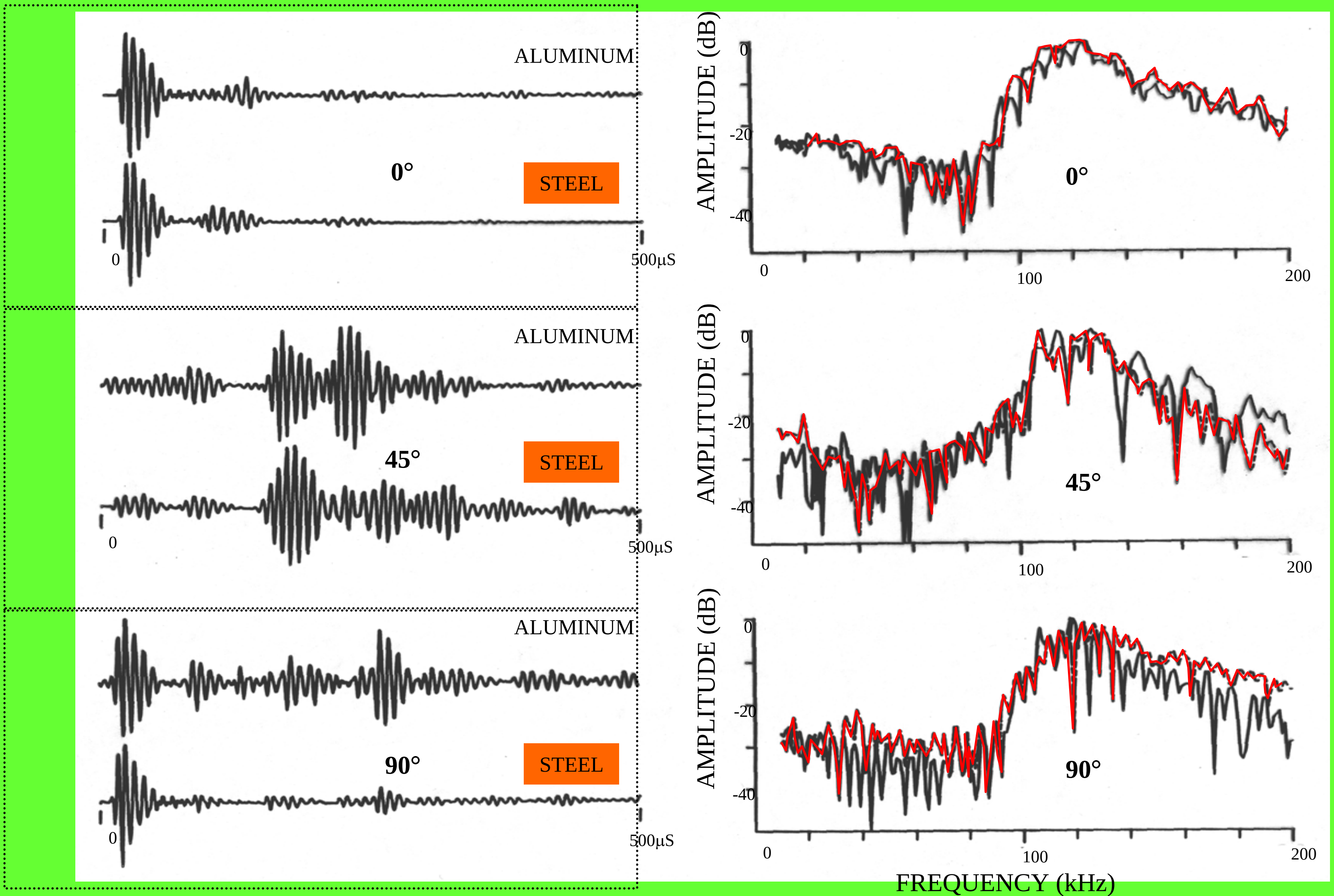
A crucial aspect of biosonar involves the structure and timing relationships between the complex highlights contained in each target backscatter

- Due to acoustic impendence targets in water are penetrable (more or less)
- Cylindrical shell example:
  - Spectral reflection from the outer shell
  - Diffracted circumferential waves
  - Elastic waves which enter into the shell and are repeatedly reflected inside the cylinder by the inner shell surfaces
  - Symmetric and anti-symmetric circumferential Lamb waves





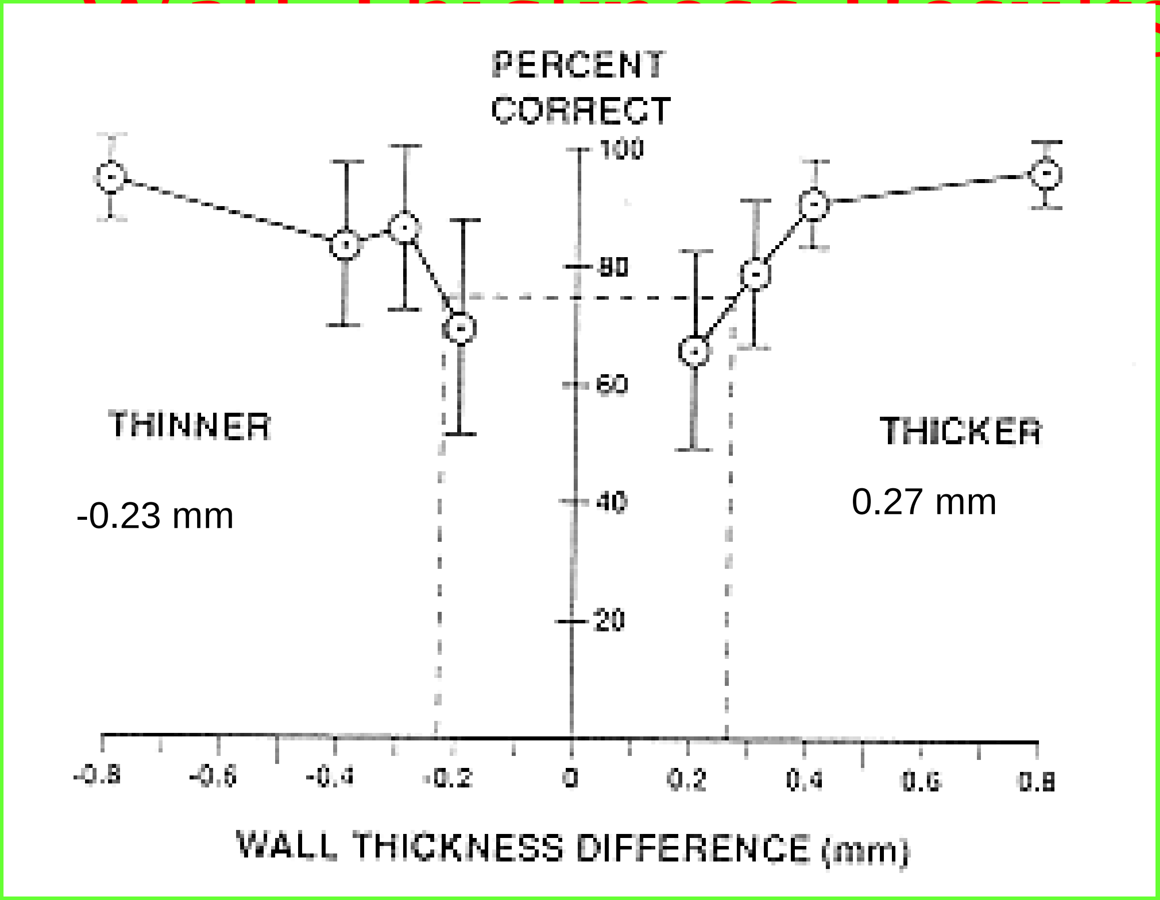
Material Discrimination



Echoes from the aluminum and steel cylinders for target aspect angles of 0°, 45°, and 90°. The echo waveforms are on the Left and the frequency spectra on the right. The dashed curves are the frequency spectra of the echoes from the steel cylinder.

Ay and Turl, 1991

Wall Thickness Results

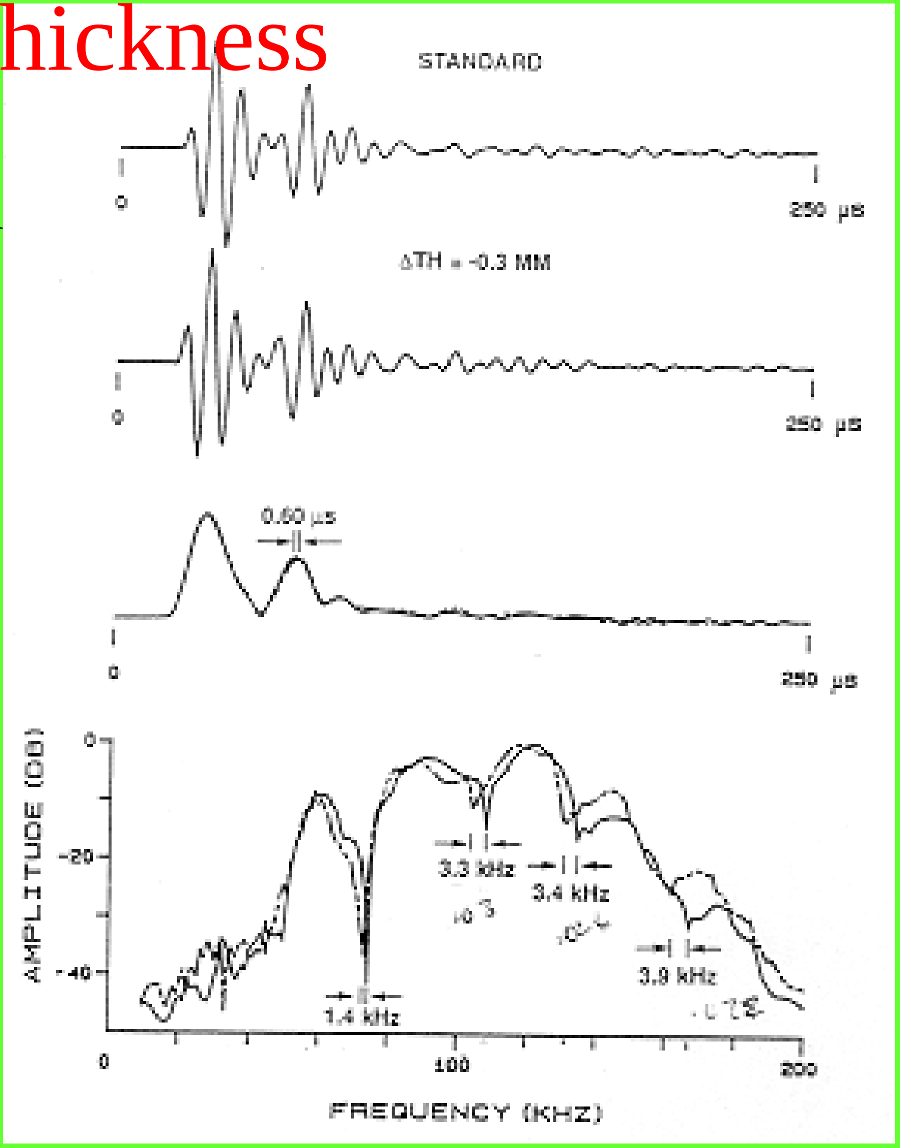


- In a thinner vs. standard (3.8 cm OD and 6.35 mm wall thickness)and then a thicker vs. standard the dolphin 75% thresholds were approx 0.25 mm

Au and Pawloski, 1992

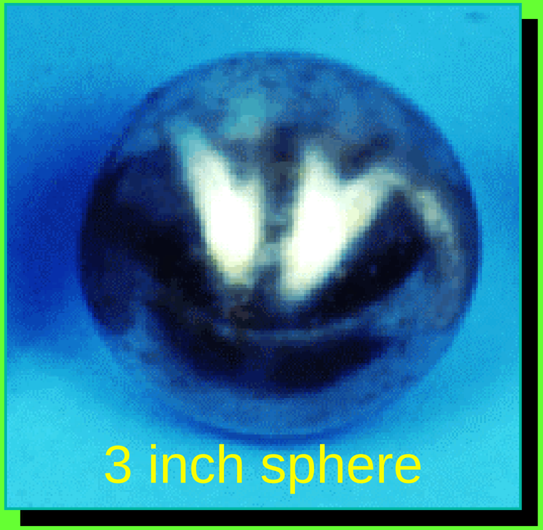
Frequency Domain Cues for Wall Thickness

- When the FFT's are examined it appears the dips in the spectra provide the cues to discriminate wall thickness…
- 1.4, 3.3, 3.4 & 3.9 kHz shifts at Approx. 75,110, 135 & 170 kHz respectively
- Frequency DL in this range are 0.5 to 0.7 % (@75kHz ~3.7 to 5.2 kHz) This does not seem to explain dolphin performance based on passive hearing experiments



DOLPHIN PERFORMANCE

- **DETECT 3" STAINLESS STEEL WATER-FILLED SPHERE AT 119m (-28dB TS)**
- **DETECT 0.2 mm WALL THICKNESS DIFFERANCE OF ALUMINUM CYLINDERS**
- **DISCRIMINATE MATERIAL**
  - **ALUMINUM**
  - **GLASS**
  - **ROCK**
  - **BRASS**
- **DISCRIMINATE SHAPE**
- **CLASSIFY TARGETS INDEPENDENT OF ASPECT**
- **DEMONSTRATE COGNITIVE SKILLS (DMTS)**



BIOSONAR PROGRAM

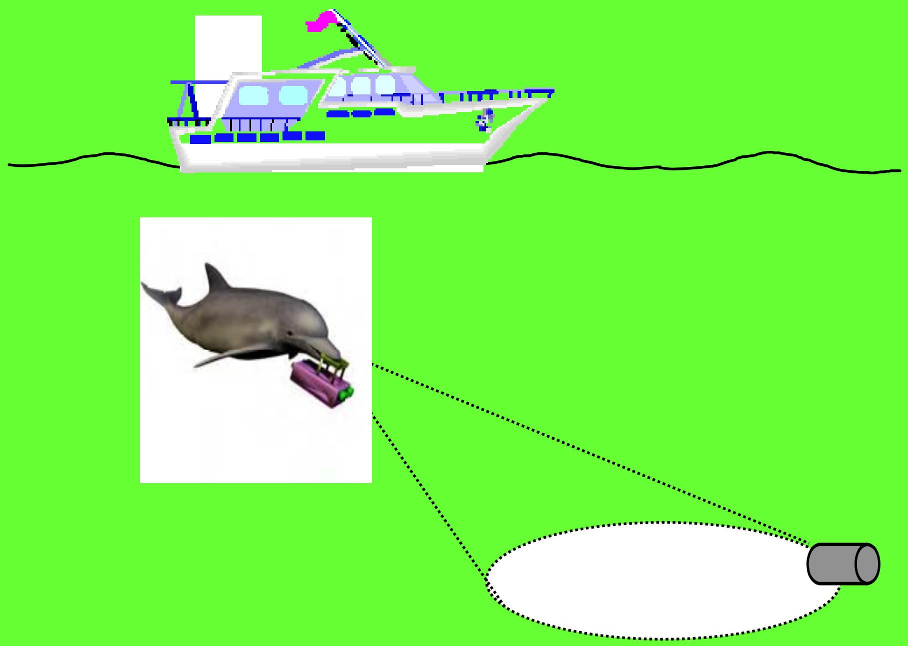
Hardware Implementation & Evaluation of Dolphin-based Biosonar Minehunting Principles

DOLPHIN BASED SONAR

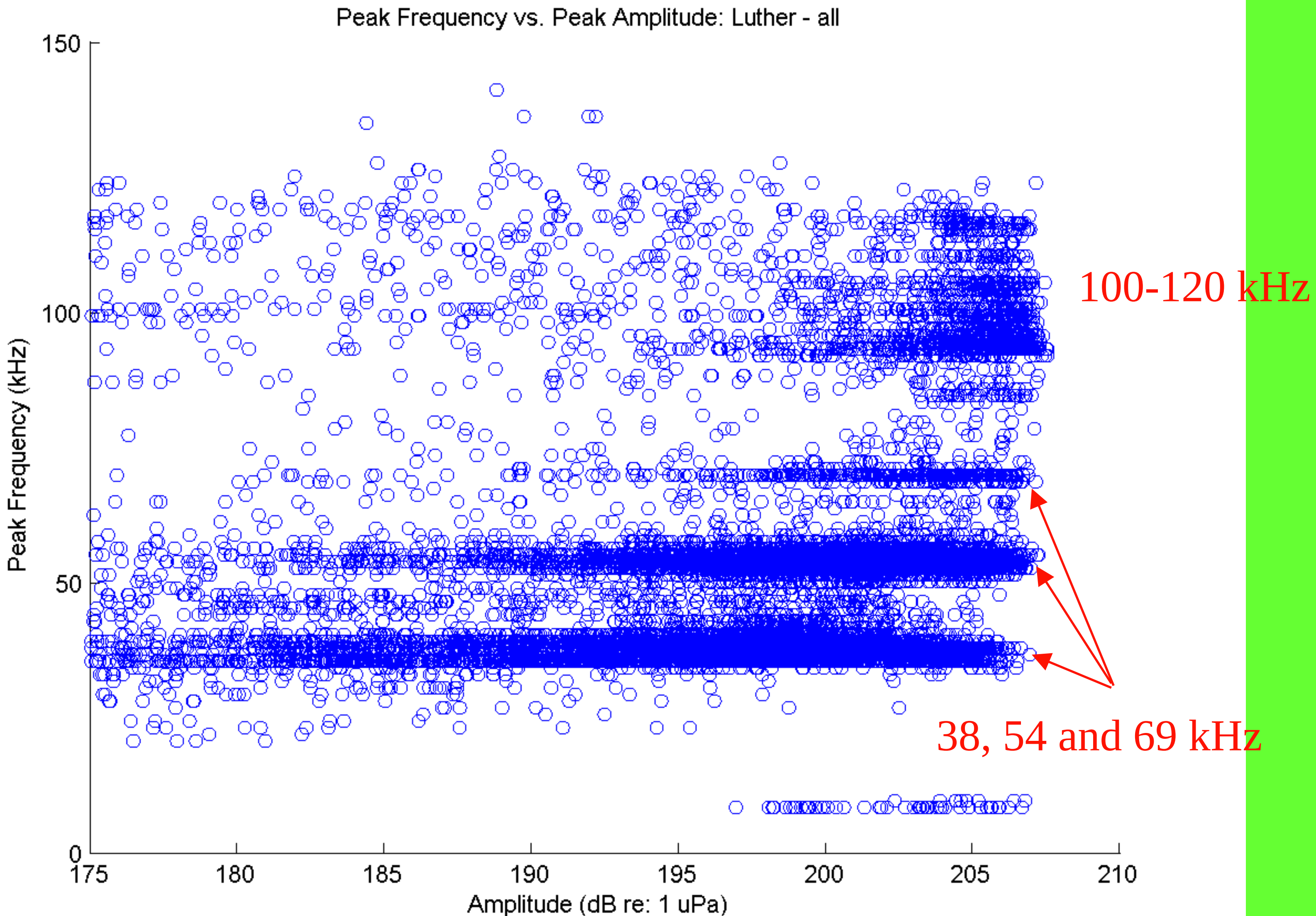
Sponsored by DARPA DSO
Controlled Biological and Biomimetic Systems

Biosonar Measurement Tool Concept
RESEARCH

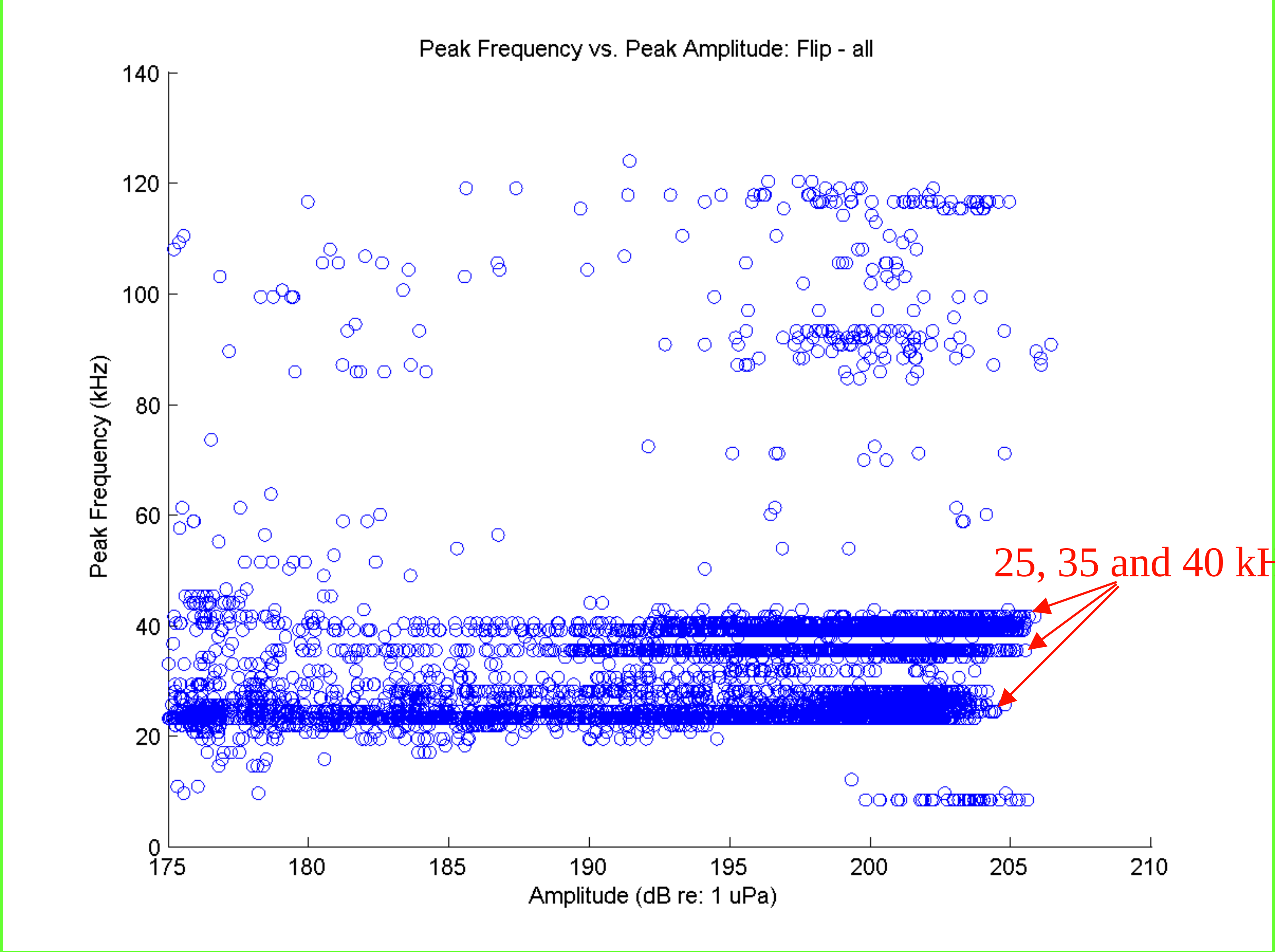
- Conduct field testing with two dolphins performing a mine hunting mission (Flip & Luther)
- Utilize BMT to collect detailed free swimming dolphin data
  - Bioacoustic emissions and echoes
  - 3D Positional Data / Hunting geometry
  - Conduct analysis of dolphin strategies
  - Animal Signals Detection with whistle
- Laboratory analysis of dolphin strategy using Virtual Reality Modeling Language (VRML)



Luther – Click Characteristics



Flip – Click Characteristics

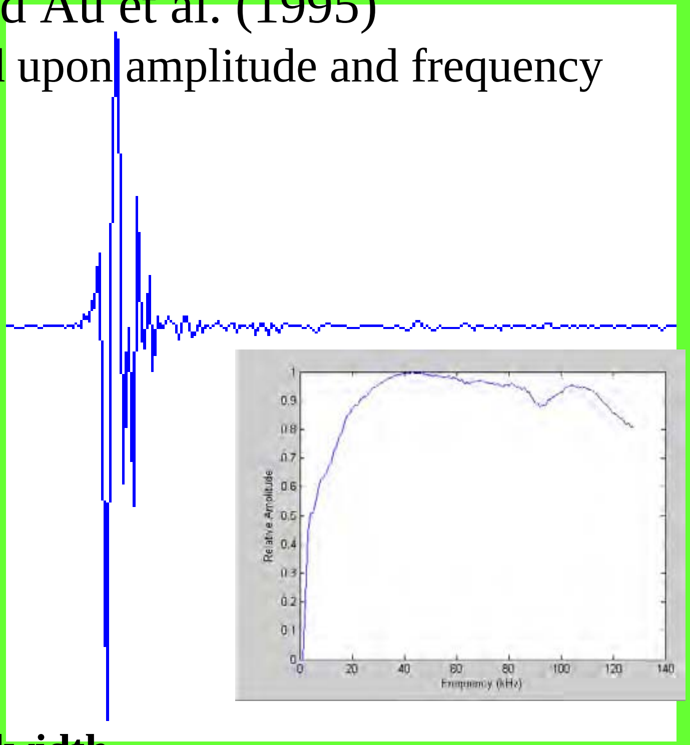


Click Taxonomy

- Based upon Houser et al. (1999) and Au et al. (1995)
  - Means of categorizing clicks based upon amplitude and frequency characteristics

  - Categories reduced to:
    - **Wideband**
    - **Low frequency, unimodal**
    - **High frequency, unimodal**
    - **Bimodal**
    - **Multimodal**

  - Criteria involve
    - **-3 dB bandwidth**
    - **Peak frequency**
    - **# of peaks within the -3 dB bandwidth**



Statistical Approach

- Analysis of Variance
  - comparison of proportional click use following modified Freeman and Tukey transform (arcsine)
- Results
  - No effect from “search” / “acquisition”
  - Strong differences in click type usage

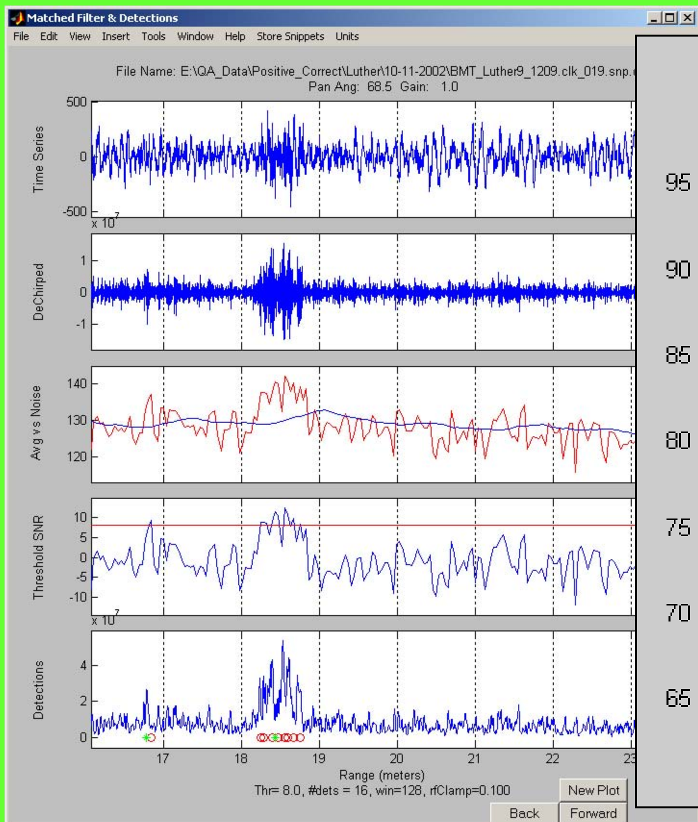
Basic Click Statistics: Luther (QA Trials)

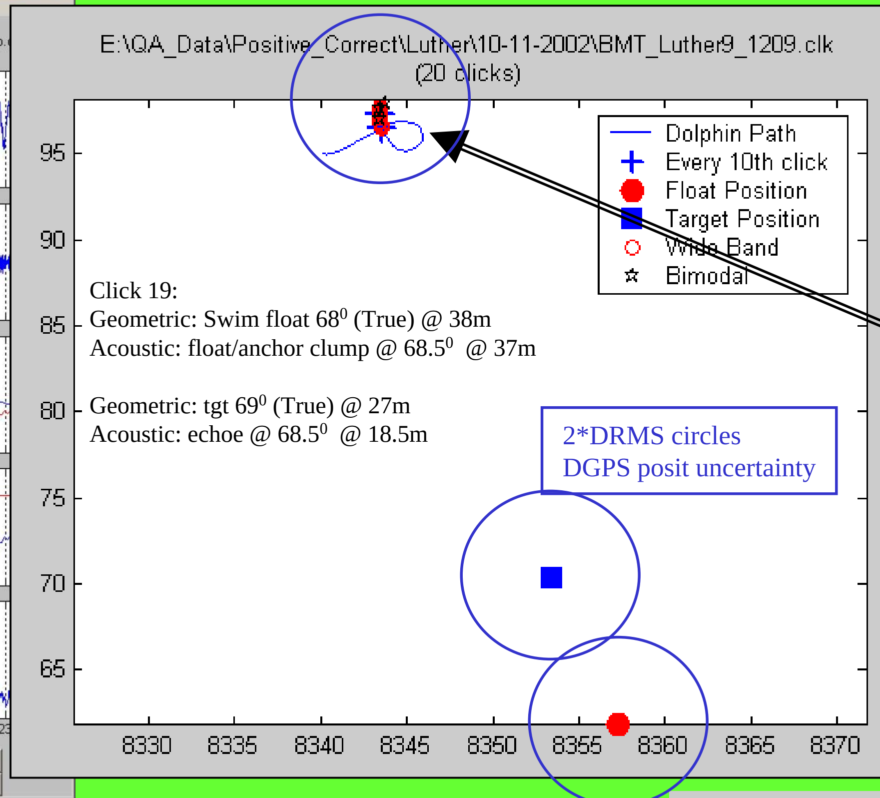
	Mean	Std Dev
W	25.2	17.8
LFU	3.13	3.3
HFU	0.8	1.4
BI	3.0	3.4
M	0.2	0.5

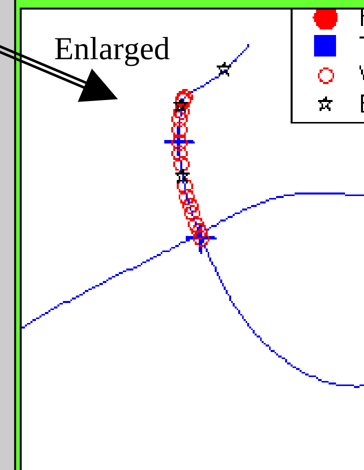
Basic Click Statistics: Flip (QA Trials)

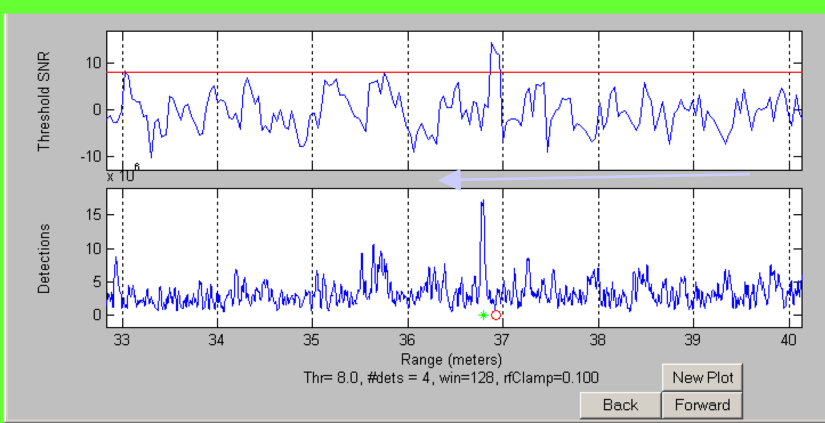
	Mean	Std Dev
W	187.8	50.2
LFU	64.6	39.8
HFU	-	-
BI	2.6	2.7
M	19	9.0

Sample of analysis Luther positive correct trial (10/11/02 #9)



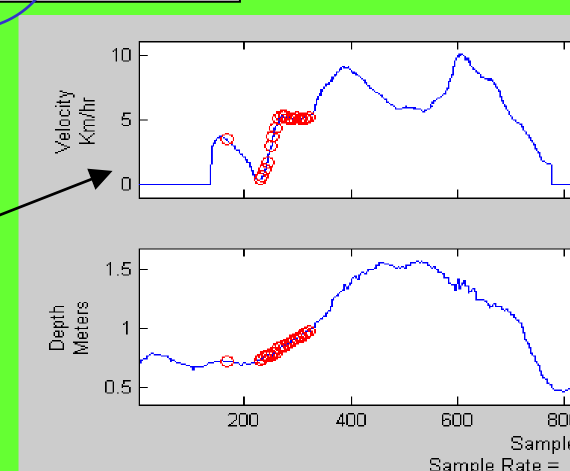




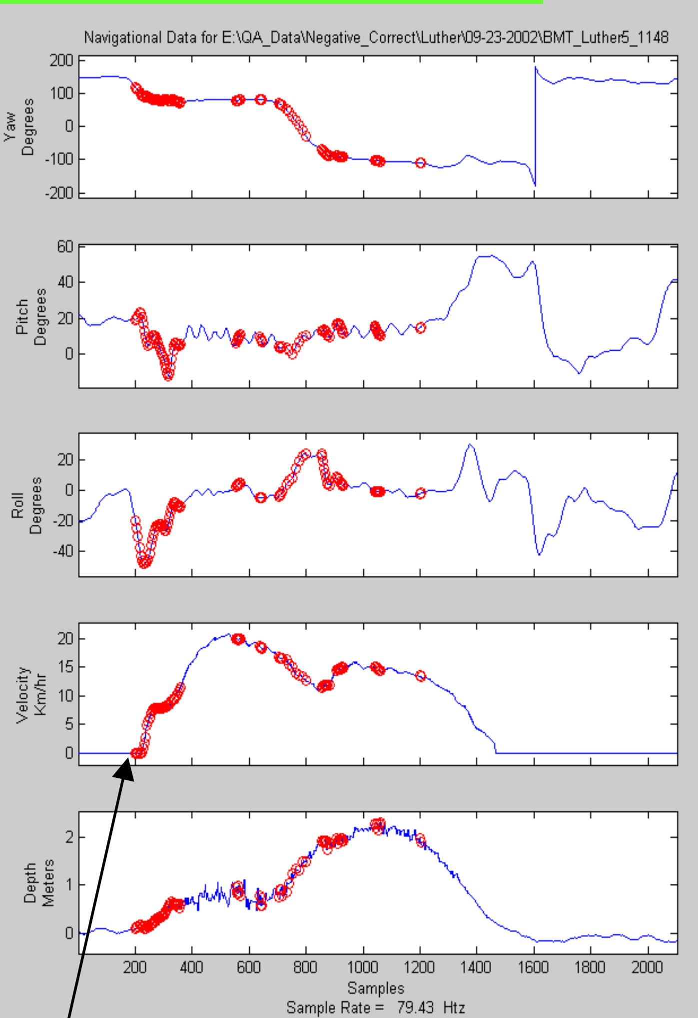


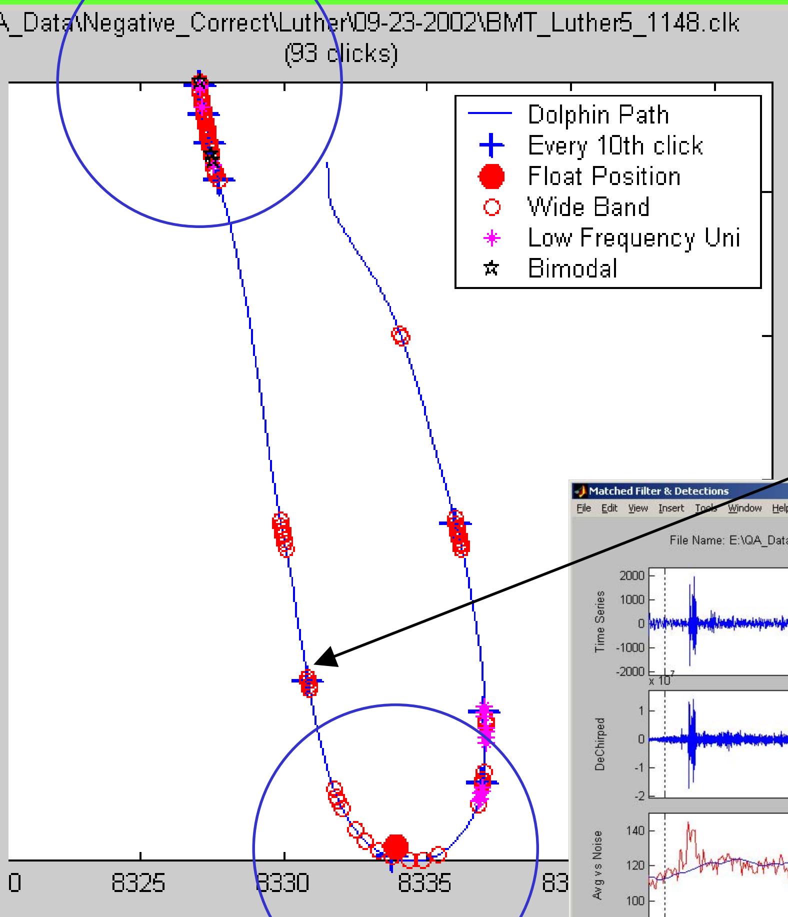
Swim float/line/anchor
Structure echo @ ~ 37m

Luther typical search from
shallow, if positive correct
Velocity < 10Km/Hr

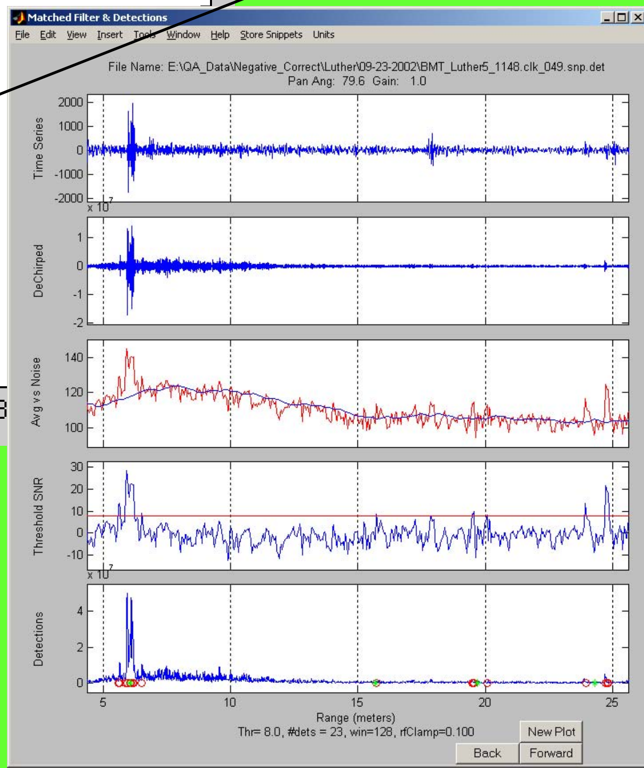


Sample of analysis Luther negative correct trial (9/23/02 #5)



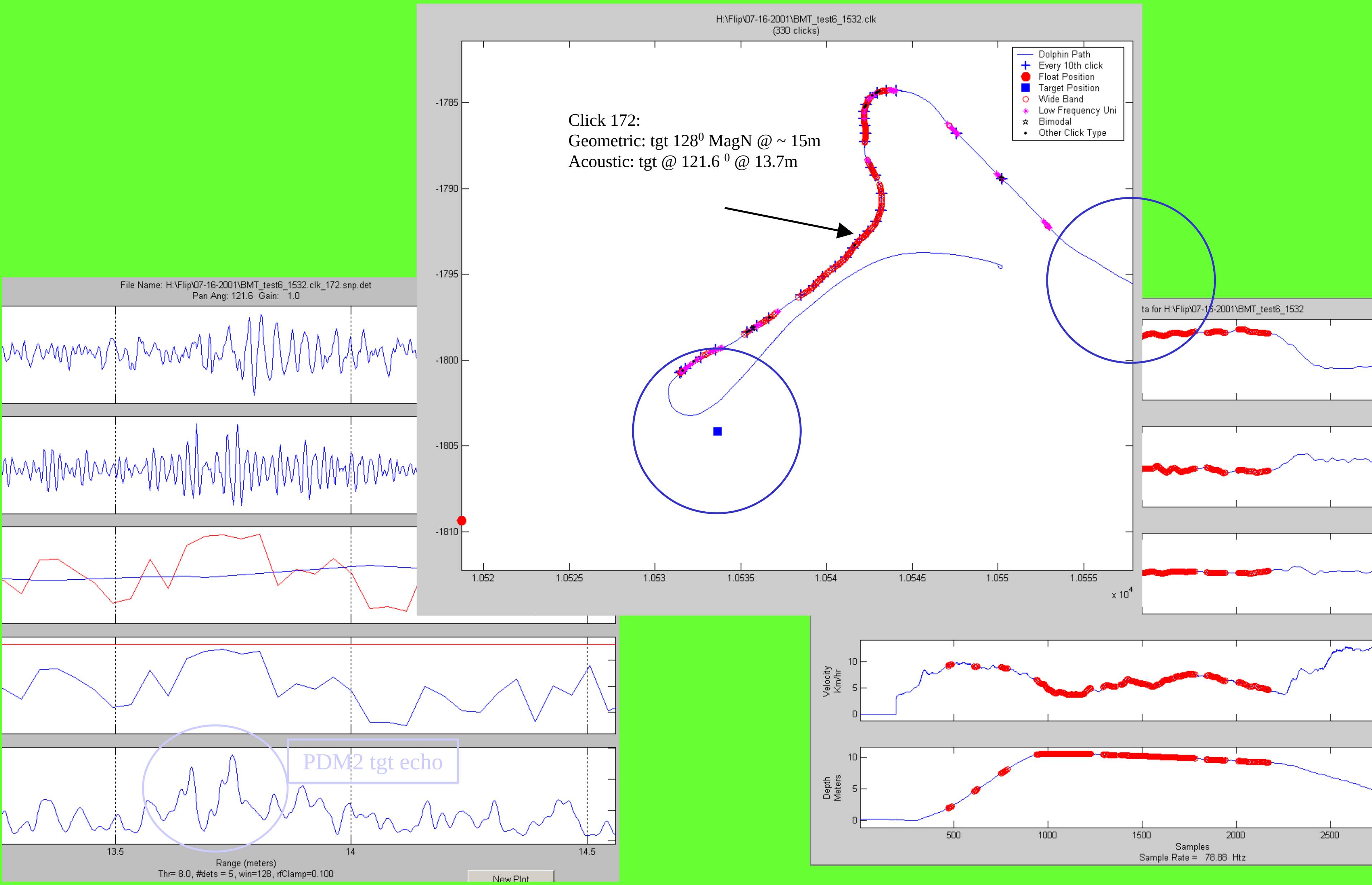


Sample of detected echoes click 49



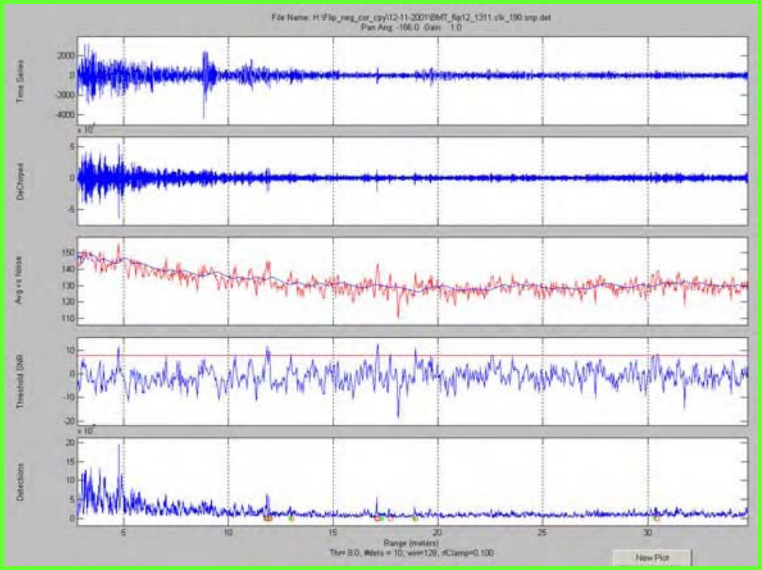
Luther typical negative correct – initial clicks
With velocity low, then speed up, with multiple
"bouts".

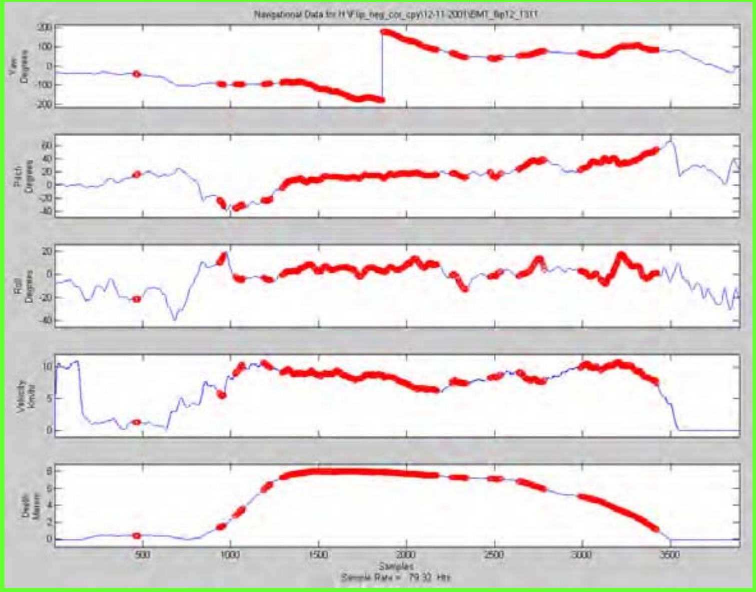
Sample of analysis Flip positive correct trial (7/16/01 #6)

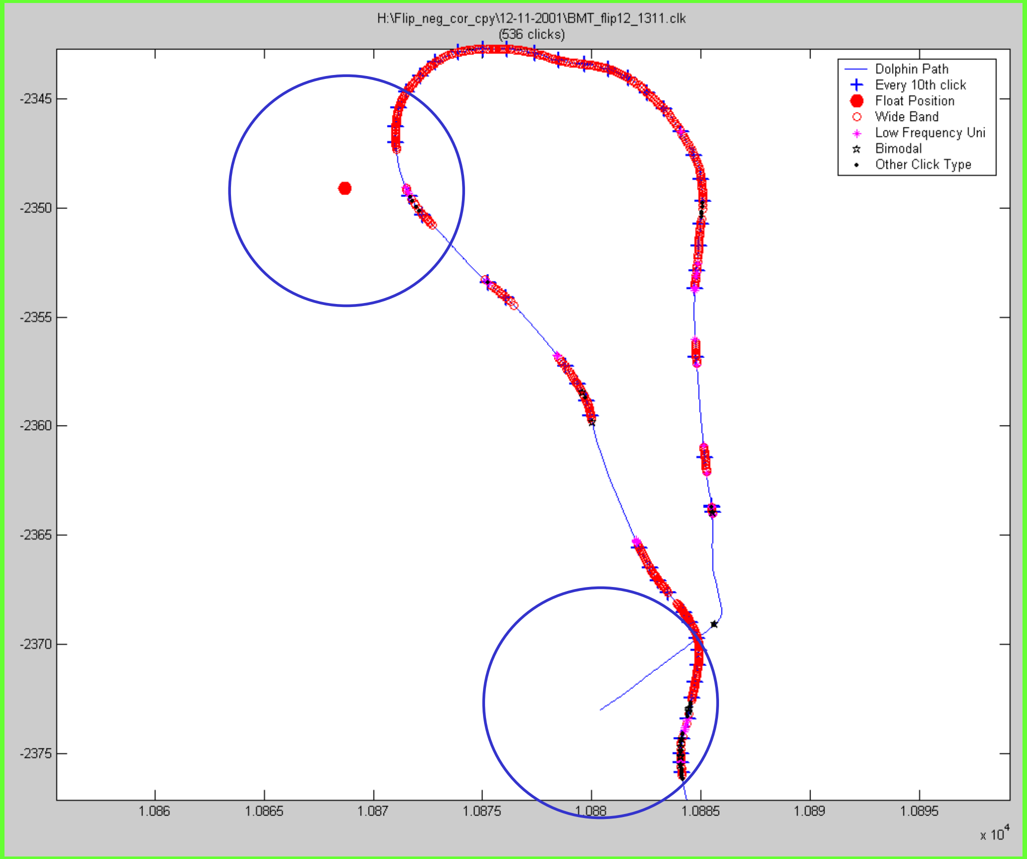


Sample of analysis Flip negative correct trial (12/11/01 #12)

Wideband click types dominate, with some LF Uni and a few bimodal types present. Velocity max around 9Km/hr (~ 4.5Knts/hr). Flip typically dives to bottom and swims along bottom while "searching".







Observations

- **Two search strategies – probable animal experience**

  “Hare” - Luther
  - Rapid decision making / conservative click production (Law of Least Effort)
  - Minimal movement on positive trials – “acoustic search completed early on and go through motions for reward?”
  - Clicks demonstrate a more variable energy-frequency distribution (relative to “Tortoise” strategy)

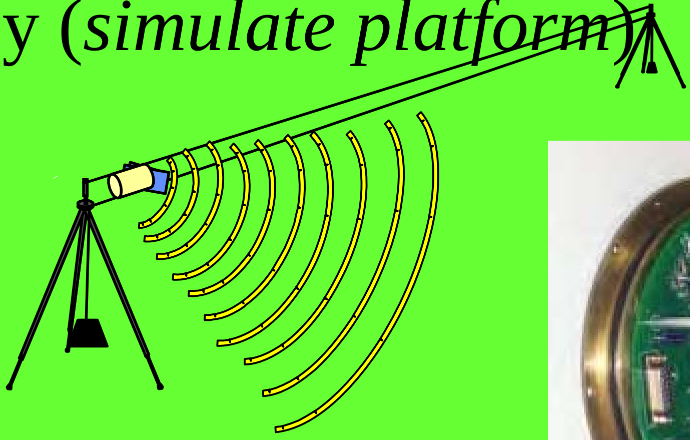
  “Tortoise” - Flip
  - 2001/early 2002: Numerous clicks production, consistent search strategy on positive and negative trials, Consistent low-frequency peaks in outgoing clicks (25 – 40 kHz), Close proximity to targets prior to whistle report (decision earlier?)
  - Late 2002/2003: Flip stops echolocating; little valid acoustic data

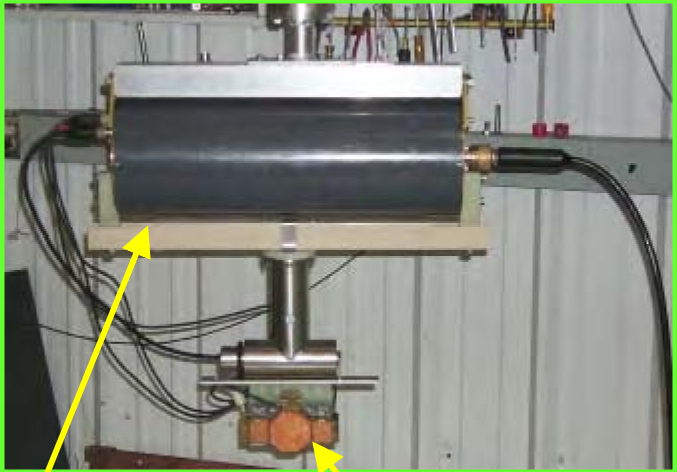
- **Both dolphins utilize wideband search strategies (-3 dB bandwidths of clicks > 85 kHz)**
  - No differences in production of clicks of a specific taxonomy between “search” and “acquisition” phases
  - Similar # of clicks emitted by Flip in both phases; significantly greater number of clicks emitted during “search” phase than in the “acquisition” phase for Luther
  - Large differences in # of clicks between two subjects
  - Searches apparent at lower swim velocities (< 4.5knots)


Unregistered HyperCam
File
Edit
View
Go
Window
Help
Back
Forward
Reload
Home
Search
Netscape
Print
Security
Bookmarks
Location:
E:\data\TESTIN~2.WRL
What's Related
Above Surface
COSMO

DBS Sonar System

- Two components: wet-end & dry-end
- ARL UT developing wet-end sonar set to specifications
- SSC SD developing dry-end & u/w trolley (*simulate platform*)

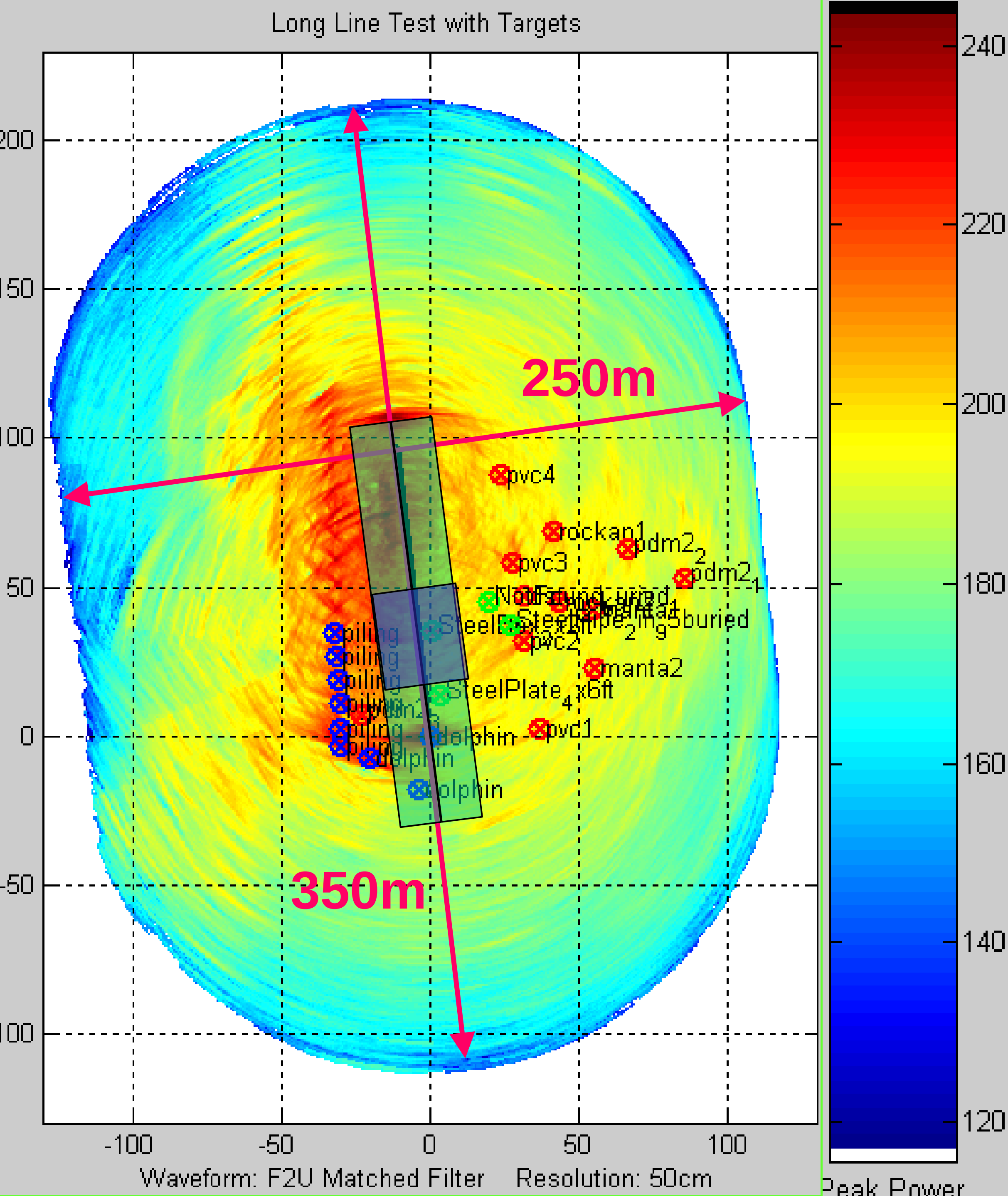




Sonar

Xmit & Rec array

- Sea tests at SSC SD
- SSC SD conduct



- Full Scale Bottom Map Of the F122 target site 350 meters by 250 meters
- Integrated energy per resolution cell 120-240 dB
- Has zoom capability to 5cm
- REMUS Marine Sonic 600 kHz side scan coverage down line shown for comparison

BioSAS SIGNAL PROCESSING

- Biomimetic Synthetic Aperture Sonar (BioSAS©) target imaging algorithm patented (U.S.N.) – runs in near-real time
- BioSAS© feature images are sensitive to interaural cross-correlation of echoes from various target points (cross-correlation images)
- Improved images of buried objects, Cross range resolution on the order of 5cm using ABF and two directional sensors

BioSAS Images of a threat mine shape

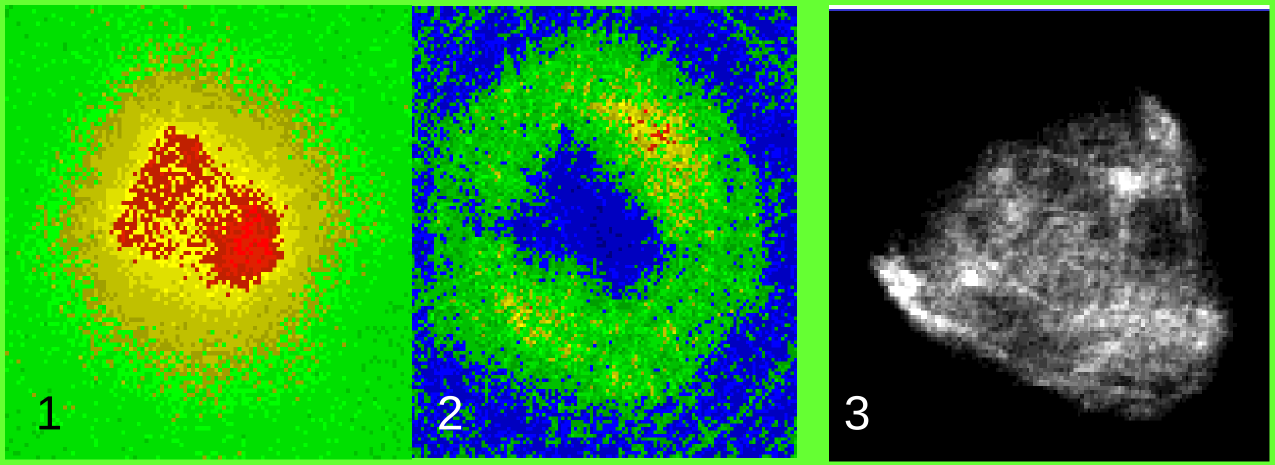
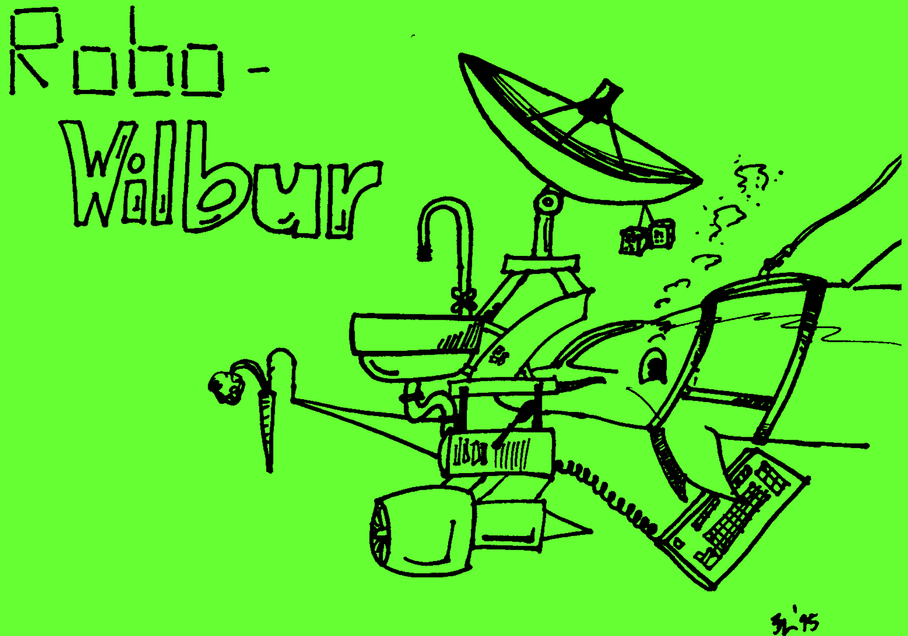


Photo of mine shape

Low grazing angle (3.5°) Of target on ARL UT LTTS rotating sediment tray
1) reflectivity images of mine object resting on a textured bottom at 75^{ft} – Darpa DBS
2) cross-correlation image of same target – Darpa DBS
3) Free-field image. ARL UT furnished signals
Aspect observation interval: 360° for all images.

NEXT STEPS ???

- We still do not know if dolphins actually form "images" of targets they echolocate
- The basic set of cues in target returns must convey some information about the target – but what information EXACTLY?



THANK YOU
ANY QUESTIONS?

Appendix 3e

Chris Clarke

Bat cochlear research

Dr C.T.Clarke

University of Bath

This work is funded by the CEC under contract IST-2001-35144 (CIRCE)

The CIRCE Project

- Chiroptera Inspired Robotic CEphaloid: a novel tool for experiments in synthetic biology
- Funding: € 2,142,000
- Project completion April 2005

CIRCE Partners

- Universiteit Antwerpen
- Friedrich-Alexander-Universität Erlangen-Nürnberg
- Katholieke Universiteit Leuven
- University of Bath
- University of Edinburgh
- Universität Tübingen
- University of Southern Denmark, Maersk McKinney Moeller Institute for Production Technology

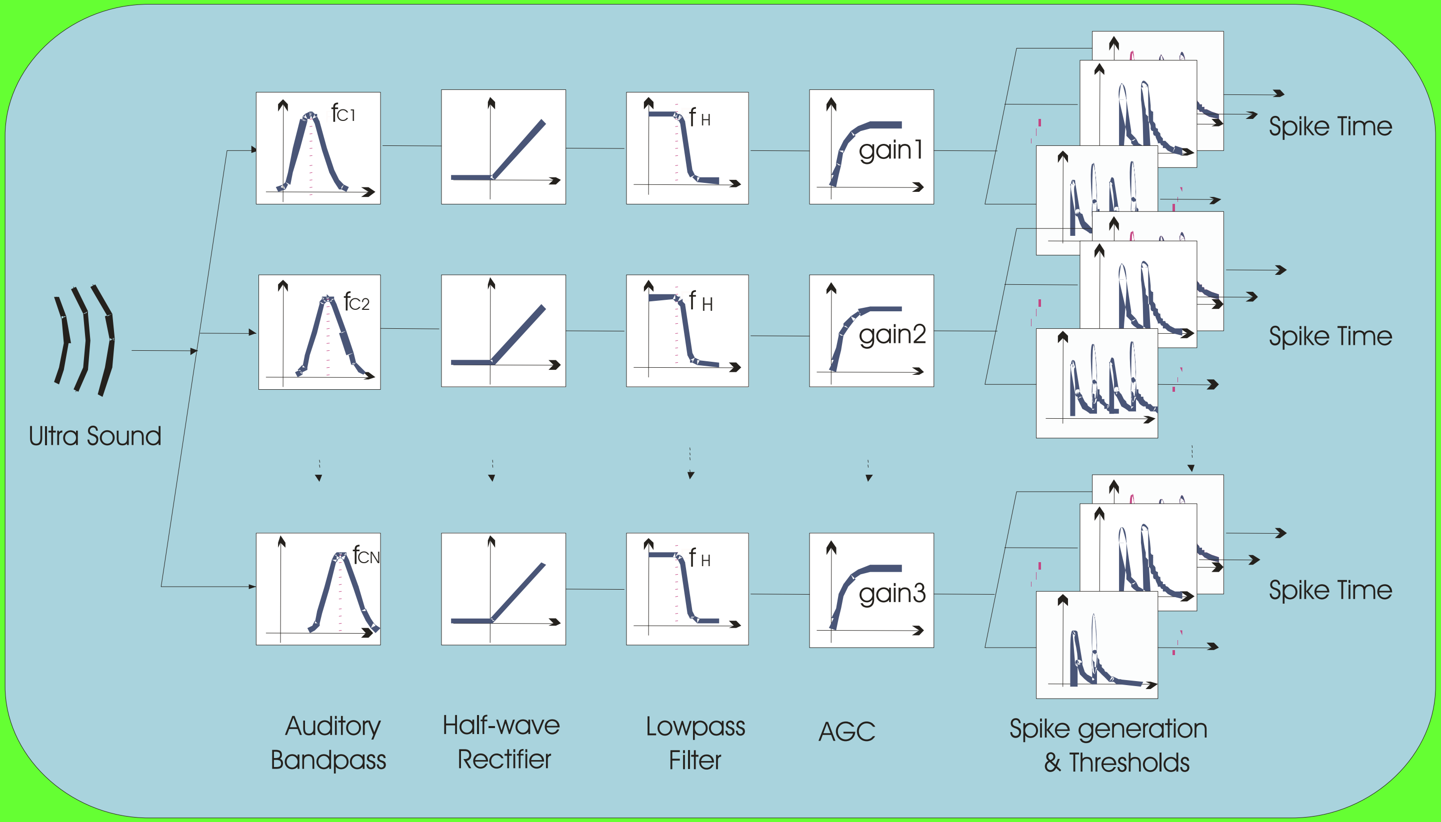
CIRCE aims

- To reproduce, at a functional level, the echolocation system of bats
- Construct a bionic bat head
  - Near life size (4-8 cm in all dimensions)
  - Processing is off head
- Investigate how the world is perceived and actively explored by bats
  - Ability to mount on a robot
  - Allows bat head to be in a control loop

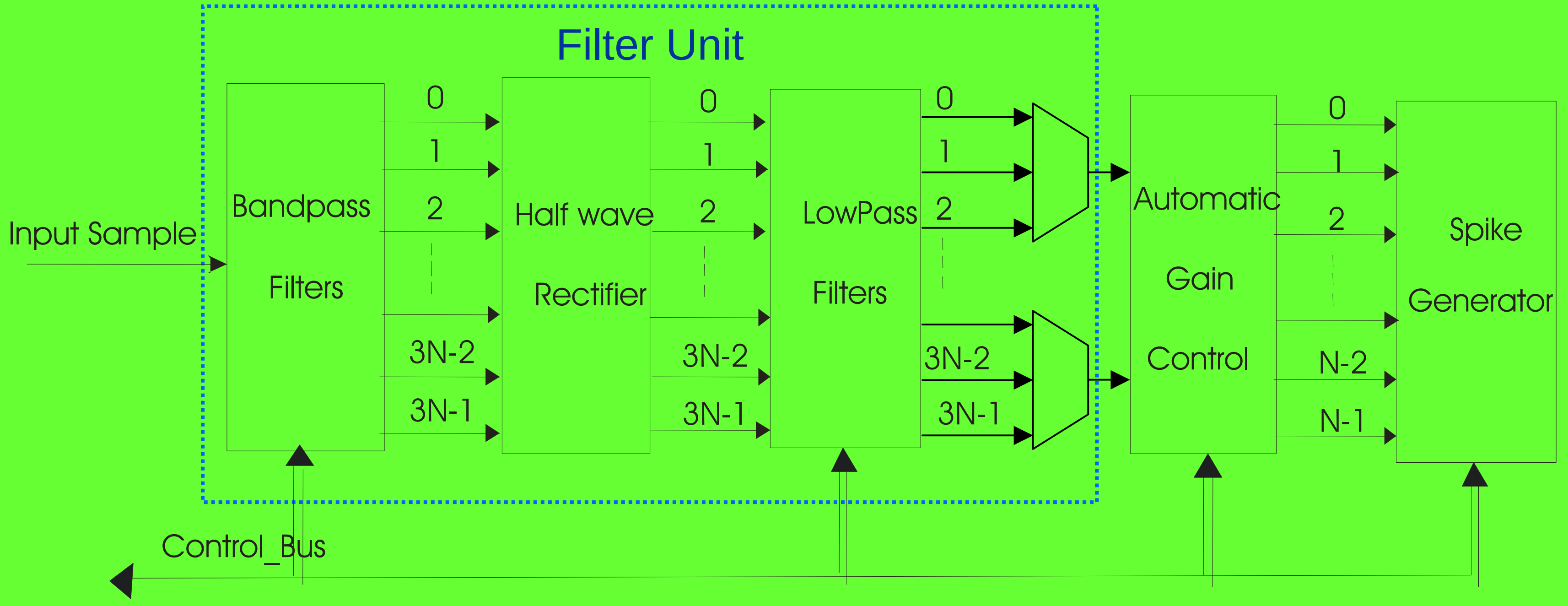
Project components

- Two ear mechanical pan and tilt system
- Rigid and morphable pinna/tragus (ear)
- Transmitter/receiver
- Transducers
- Synthetic bat cochlea
  - Designed at University of Bath
- Experimentation phase

Biomimetic Cochlear

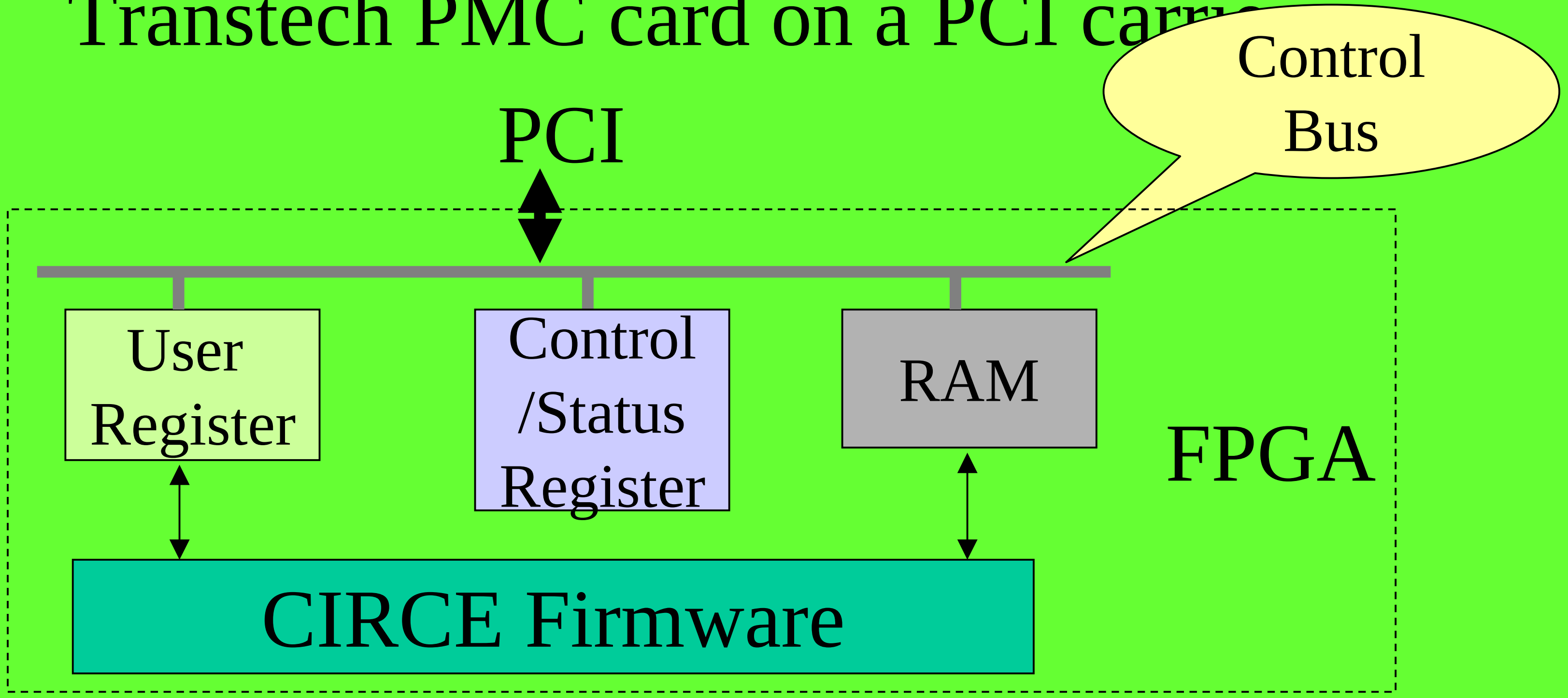


Top level blocks

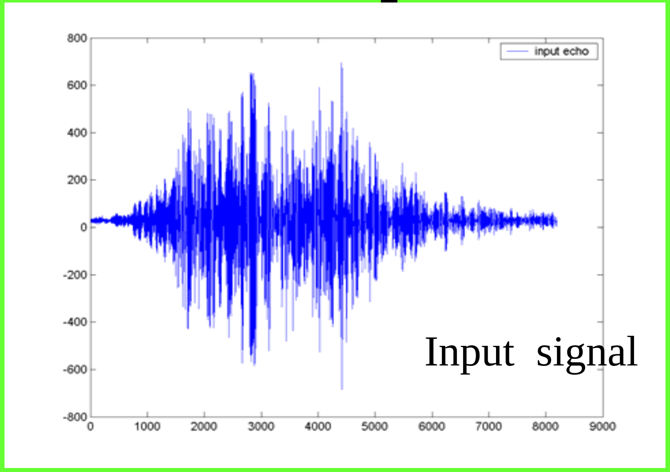


PCI Interface

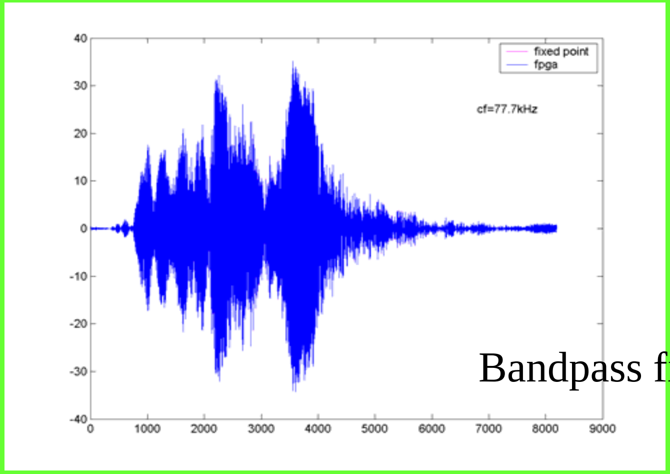
- Design implemented on a standard Transtech PMC card on a PCI carri



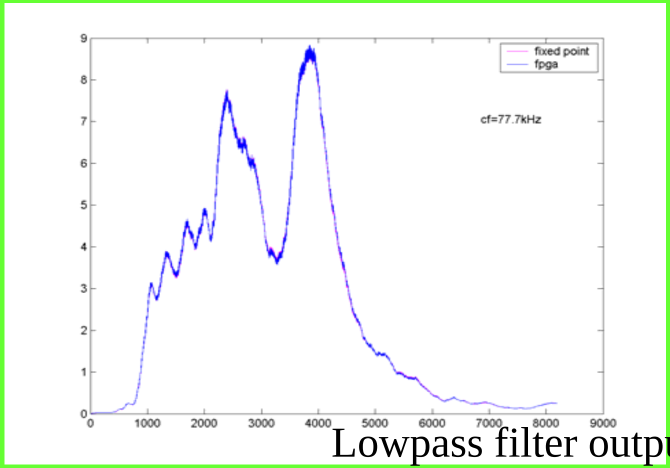
Experimental Results



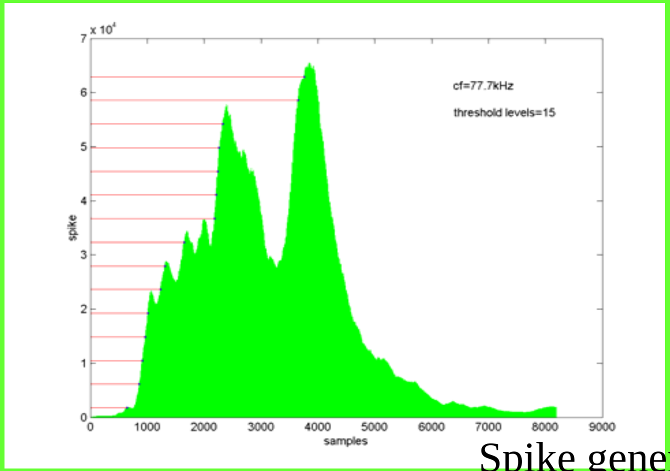
Input signal



Bandpass filter output



Lowpass filter output



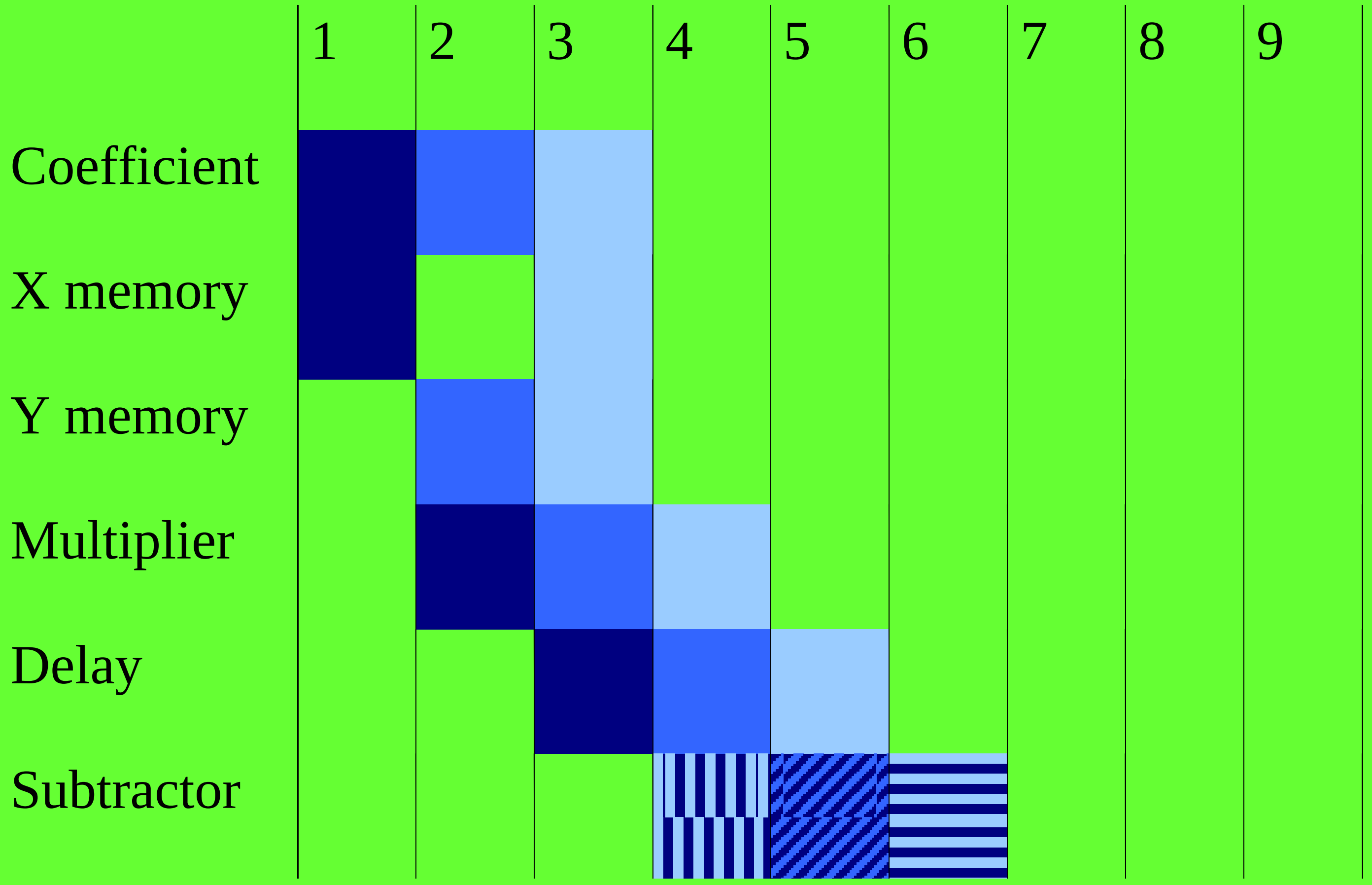
Spike generation output

FPGA Implementation

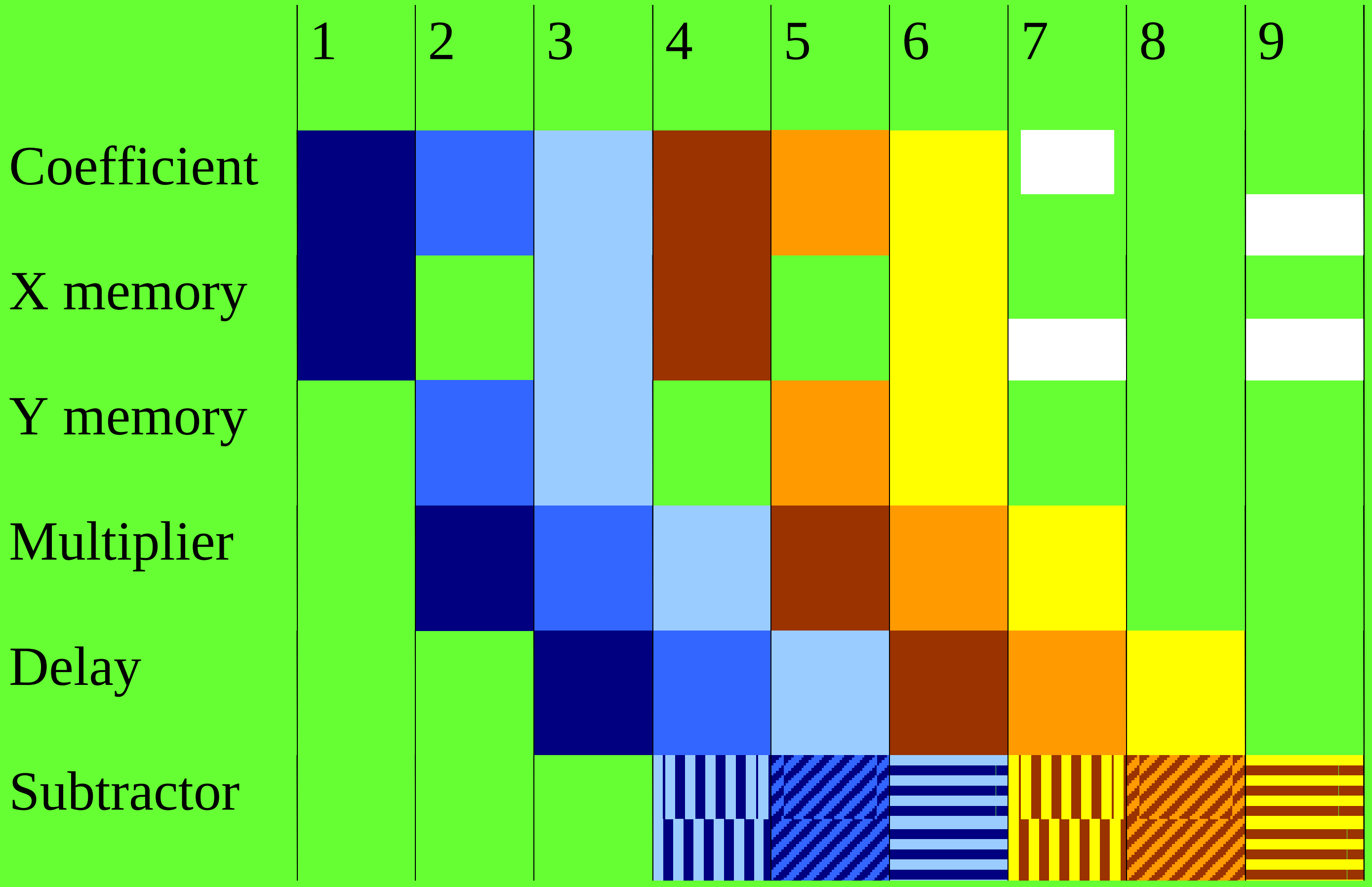
- 300 filter continuous operation
- 16 spikers/filter
- 80MHz clock 1MHz sample rate

```
Device utilization summary:
Number of External IOBs            112 out of 824     13%
Number of LOCed External IOBs      112 out of 112    100%
Number of MULT18X18s                52 out of 144     36%
Number of RAMB16s                  129 out of 144     89%
Number of SLICEs                 12106 out of 33792   35%
Number of BUFGMUXs                   2 out of 16      12%
Number of DCMs                       1 out of 12       8%
Number of TBUFs                    313 out of 16896    1%
```

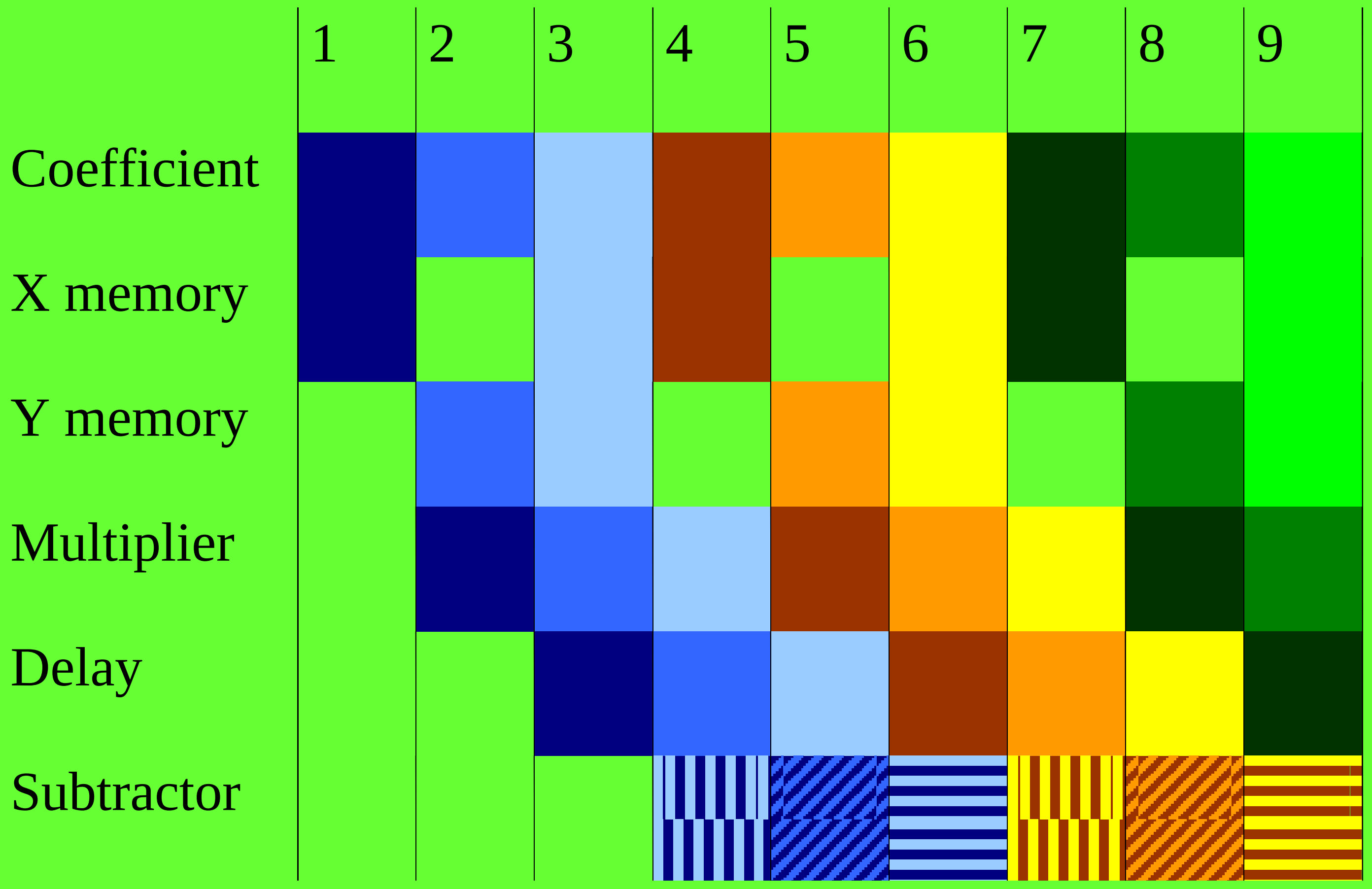
Filter Implementation



Filter Implementation



Filter Implementation



Projected implementation

- Optimised implementation
  - 1200 filters in continuous operation
  - 3000 filters per ear for 20% duty cycle
  - Multiple retriggerable spikers per filter channel
- Compute requirement beyond single DSP capabilities
  - 30G ops/s
  - 7G multiplies/s
  - 5GBytes/s sustained data throughput

Conclusions

- The CIRCE project is implementing a full biomimetic bat head to allow experimentation
- FPGA based synthetic cochlear exists today
- Experimentation will modify only basic parameters of the synthetic cochlear
- Further research needed to establish the relationship between system requirements and implied cochlear complexity

Appendix 3f

Laurie Linnett

Chirp Signal Processing

FORTKEY LTD

WHY LOOK AT CHIRP SIGNALS?

- Chirp signals occur frequently in nature and are used by bats and dolphins.
- As well as using chirps because they occur in nature, we use them because they have good pulse compression properties.
- Pulse compression was developed in the 1940's in radar applications. The first patent was issued in 1953 (it was filed in 1945 by R H Dicke in the USA).

WHY LOOK AT CHIRP SIGNALS? (cont'd)

- It allowed detection performance to be the same for a long low power pulse as for a short high power pulse, e.g. a 0.25mS pulse of 2kW gives the same detection performance as a 5mSpulse of 100W, both having the same energy of 0.5 Joules.
- It is defined in IEEE standard 686-1990 as *"The processing of a wideband, coded signal pulse, of initially long time duration and low range resolution, to result in an output pulse of time duration corresponding to the reciprocal of the bandwidth and, hence higher range resolution, and with approximately the same pulse energy"*.

Paradoxes

- Several paradoxes currently exist:
  1. Bats and dolphins use low power whereas man usually needs to inject proportionately larger quantities of power.
  2. Bats operate at typically 80 KHz at a bandwidth of 40 KHz yet can resolve to 10 nS in time.
  3. The arrays used by mammals are significantly smaller than man made arrays.

WHAT IS A CHIRP?

- A chirp is a signal that varies its frequency with time
- It may be represented mathematically as

$$f(t) = e^{jg(t)}$$

- *g(t)* is a function of time, for example

$$g(t) = (a/2)t^2 + bt$$

- The complex part of *f(t)* is the phase and the derivative of the phase is the instantaneous frequency. In this case $g'(t)=at+b$
- In this case *g'(t)* is linear and *f(t)* would be a linear chirp
- Other functional forms of chirp occur

MULTIPLE CHIRP SIGNAL ANALYSIS

- What are chirp signals and why use them
- Methods for analysing chirp signals
- Fourier transform extensions
- Signal filtering and reconstruction
- Applications of Chirp Analysis

THE FOURIER TRANSFORM

- Taking the Fourier Transform (FT) of a time (*t*) signal we get a frequency (*f*) signal. We can think of this as moving through 1 right angle (*t* and *f* are orthogonal) from *t* to *f*.
- Repeating this to go from *f* to –*t* we have performed 2 FT's.
- A 3rd FT takes us form –*t* to –*f*
- Finally a 4th FT takes us from –*f* back to *t*
- So 4 FT's return us back to our original signal and we can say the FT is a modulo 4 integer transform.
- Does a non-integer FT exist?

FOURIER ANALYSIS

- Fourier Analysis is the natural tool for analysing sinusoids.
- A sinusoid may be represented mathematically as
- *g(t)* is a function of time, for example

$$f(t) = e^{jg(t)}$$

$$g(t)=bt$$

- The complex part of *f(t)* is the phase and the derivative of the phase is the instantaneous frequency. In this case *g'(t)=b*
- In this case *g'(t)* is of 0 order and *f(t)* would be a constant with time.

Methods for Looking at Time Varying Signals

- Probably the most common method is the short-time Fourier transform (STFT)
- This windows out a section of the data (concentrates about that point in time) and then Fourier transforms that section to give a time-frequency representation of the data

$$F_\tau(\omega) = \int_{-\infty}^{\infty} f(t)\,g(t-\tau)\,e^{-j\omega t}\,dt$$

- There are many variants on this theme. The problem to solve is how can we determine the parameters of signals whose frequencies vary with time.

The Fractional Fourier Transform (FrFT)

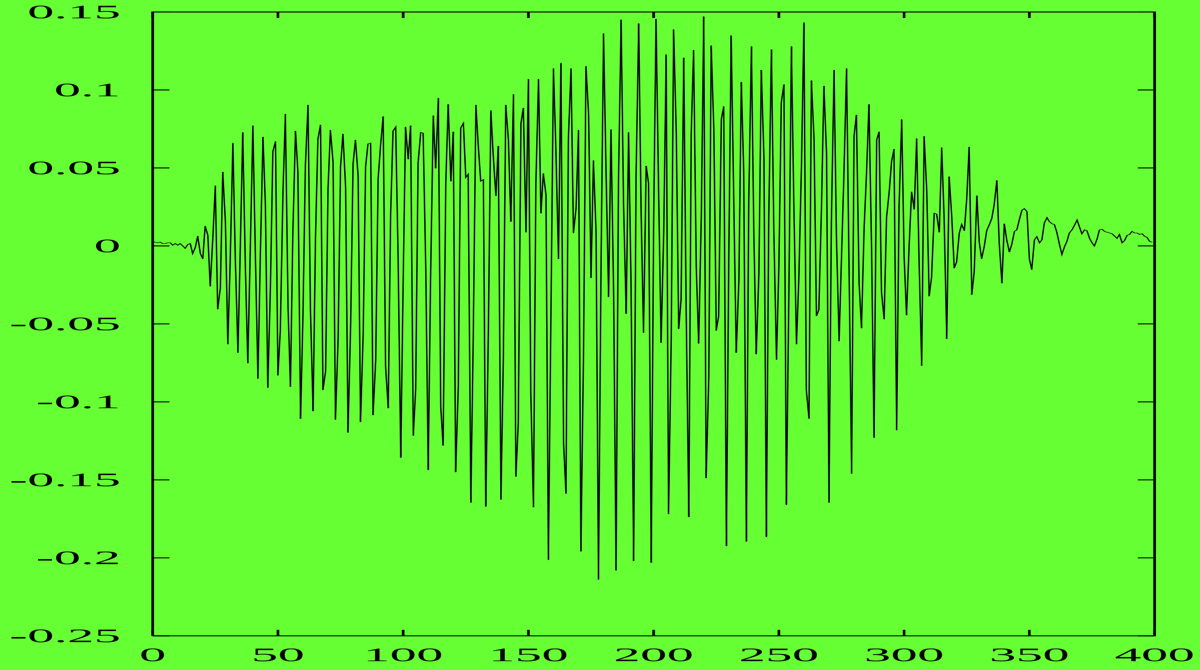
- In operator notation we write the FT as $F^n(f(t))$ where n is 1,2,3 or 4
- We can make n fractional and this corresponds to a rotation by an angle α
- The full equation of the fractional Fourier transform is

$$F^{\alpha}(f(x)) = \frac{\exp(-j(\pi/4-\alpha/2))}{(2\pi|\sin\alpha|)^{1}/2}\exp(\frac{1}{2}jx^{2}\cot\alpha)\times$$

$$\int_{-\infty}^{\infty}\exp(\frac{-jxy}{\sin\alpha}+\frac{1}{2}jy^{2}\cot\alpha)f(y)dy$$

- This is
  1. Multiplication by a chirp
  2. A Fourier Transform
  3. Another multiplication by a chirp
  4. Multiplication by a complex scaling factor

A Multiple Chirp Signal From Nature



2.5ms Bat chirp signal

- The data is by courtesy of Curtis Condon, Ken White and Al Feng of the Beckman Institute of the University of Illinois.

Fourier Extensions for Chirp Analysis

- In the Fourier Transform we isolate a frequency component by multiplying by that frequency. Our signal may be thought of as $\sum e^{jb_i t}$. To isolate or analyse for a particular frequency (b_k) we multiply by $e^{-jb_k t}$

- We can use a similar trick to isolate our linear chirps. Our signal may be thought of as $\sum e^{j((a_i/2)t^2+b_i t+c_i)}$. To isolate or analyse for a particular chirp (a_k) we multiply by $e^{-j(a_k/2)t^2}$ and then Fourier transform the result.
- If a chirp is present at that rate we will obtain a response, just as in conventional Fourier analysis.
- We proceed through all necessary chirps in this manner breaking down our signal into its individual linear chirps.

Fourier Extensions for Practical Chirp Analysis

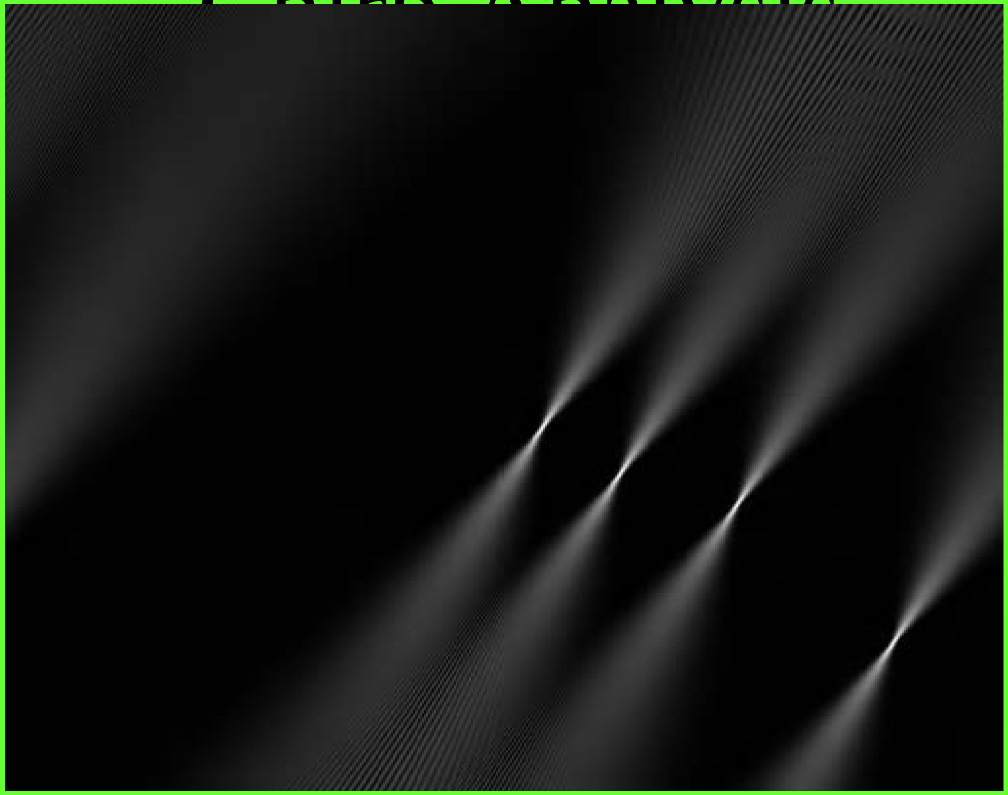
- To illustrate the algorithm, the following four chirps given in the table were constructed and analysed to produce the magnitude image shown in the figure.

amplitude	t_1	t_2	f_1	f_2
100.0	0.0	2.0	10.0	20.0
100.0	0.0	2.0	30.0	55.0
100.0	0.0	2.0	60.0	95.0
100.0	0.0	2.0	100.0	180.0

Chirp parameters used in Fourier Extension Algorithm Example

- The total sample time was $T=2.0$ seconds and $N=512$, a Gaussian envelope was used in the signals.

Fourier Extensions for Practical Chirp Analysis



Fourier Extension Image

- As can be seen we have 4 distinct highlights in the image. These correspond to the four chirps.

Time Resolution Between Two Linear Chirps

- We consider two chirps of the same rate with start positions separated by *dT* seconds. If they were of different rate we would also have separation in the rate direction

$$\exp(j(\frac{a}{2}t^2)), \exp(j(\frac{a}{2}(t+dT)^2))$$

i.e. linear chirps, $f=at$ and $f=a(t+dT)$ separated by adT in frequency at $t=0$.

- Let our analysing chirp be $\exp(-j\frac{a}{2}t^2)$. Multiplying our signal consisting of two linear chirps by this analysing chirp produces two frequency components, one at DC, corresponding to chirp 1, and one at adT, corresponding to chirp 2.
- Our frequency resolution is f_s/N, thus for separation we require $adT= f_s/N$, therefore

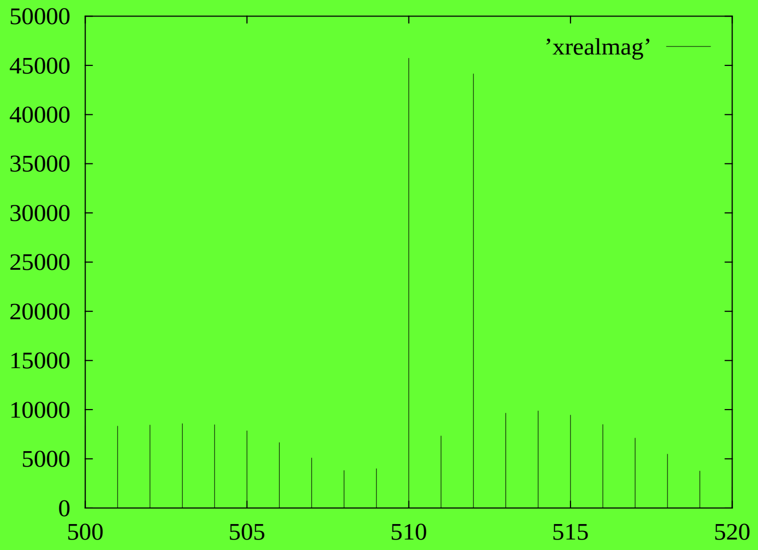
Chirp time resolution = $dT= f_s/(aN)=1/(aT)$

- This will result in two residual frequency peaks being in two adjacent frequency bins. If we require them to be separated by 2 frequency bins, then $dT=2/(aT)$.

Time Resolution Between Two Linear Chirps

- As an example consider the following two chirps:

T	10 sec
N	1024
$f_1 start$	0 Hz
$f_1 end$	9 Hz
$t_1 start$	0 sec
$t_1 end$	9.0 sec
$f_2 start$	0 Hz
$f_2 end$	9 Hz
$t_2 start$	0.2 sec
$t_2 end$	9.2 sec
$a_1 = a_2$	1.0 Hz /sec



- The position for chirp 1 is 0 ($b = f_1 start = 0$), and the position for chirp 2 is ($b - a t_2 start)T = (0 - 1.0 * 0.2)10 = -2$, i.e. the chirps are separated by 2 frequency samples, as predicted by the equation given above. This is illustrated above where the peaks occur at 512+0=512 and 512-2=510.

Rate Resolution Between Two Linear Chirps

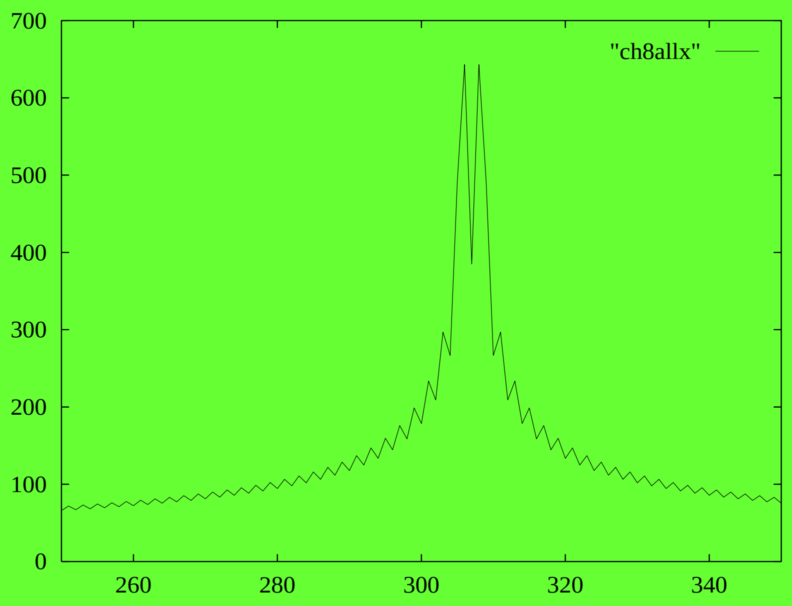
- The fastest chirp occupying the total length of the signal that can be represented without aliasing has rate $a=f_s/2T$.
- The slowest chirp occupying the total length of the signal (apart from a zero rate chirp, i.e. a sinusoid) corresponds to the rate $f_s/(NT)$. All the other possible chirps can then be considered as part of the set with rate given as $a_k=kf_s/(NT)$, $k=0\ldots N/2$.
- In theory two chirps can be separated when their rates differ by $da=f_s/(NT)$ (i.e. when the optimal transform for each chirp occurs in adjacent rate bins).

Chirp rate resolution = $da=f_s/(NT)=1/T^2$

Rate Resolution Between Two Linear Chirps

- Consider the separation of the following two chirps:

T	10 sec
N	1024
$f_1 start$	0 Hz
$f_1 end$	5 Hz
$t_1 start$	0 sec
$t_1 end$	10 sec
$f_2 start$	0 Hz
$f_2 end$	5.1 Hz
$t_2 start$	0 sec
$t_2 end$	10 sec
a_1	0.5 Hz /sec
a_2	0.51 Hz /sec



- In this example $da=f_s/NT=(N/T)/(NT)=1/T^2=0.01$. If $da<0.01$ we could not resolve the peaks.
- The result of the analysis is shown in the figure above, which is a plot of amplitude versus order of transform.

Separation of Chirps on the Same Time-Frequency Line

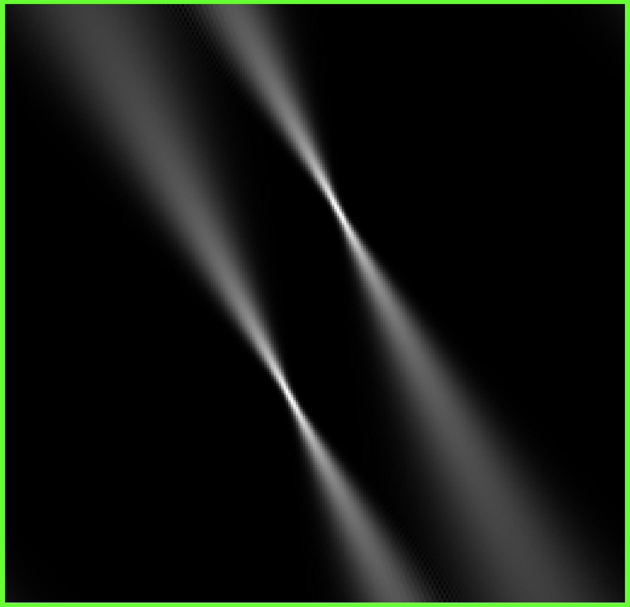
For a Gaussian with a mean position t_c the time signal may be represented as

$$f(t) = 1/(2\pi\sigma^2)^{1/2} e^{-(t-t_c)^2/(2\sigma^2)+j\beta t^2/2+j\omega_0 t} \tag{1}$$

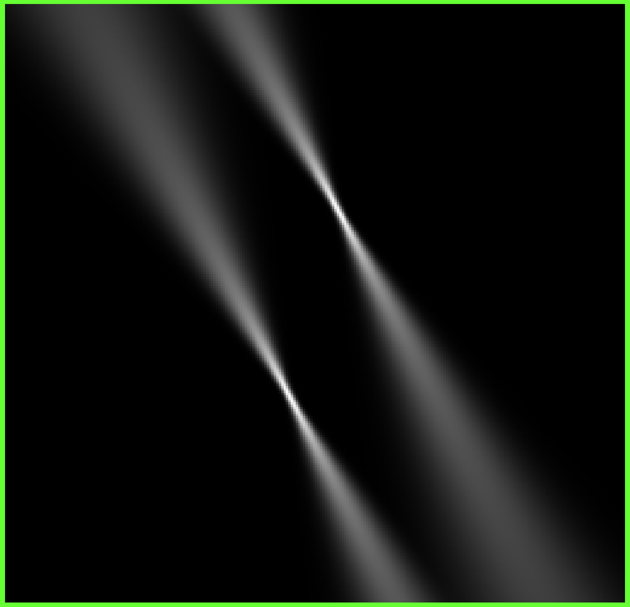
The energy density spectrum turns out to be

$$|F(\omega)|^2 = \sqrt{\frac{1}{1+\beta^2\sigma^4}} \exp\left[\frac{-\sigma^2((\omega-\omega_0)-t_c\beta)^2}{(1+\beta^2\sigma^4)}\right] \tag{2}$$

Comparison of Theoretical and Actual Spectra



(a) Theoretical



(b) Actual

Separation of Chirps on the Same Time-Frequency Line

- To see the effects of this consider the signal shown in the figure below. It is the signal of a chirp occupying the time slot from 1 to 2 seconds and frequencies 5 to 7 Hz and also a chirp occupying the time slot from 3 to 4 seconds and frequencies 9 to 11 Hz. That is both chirps have the same rate and occupy the same residual frequency bin given by $(b\text{-}at_1)T$=12. That is at the correct analysing chirp rate, both have rate zero and hence cannot be separated at this point. However, away from the correct analysing chirp the two chirps may be separated. The maximum occurring at $\omega = \omega_0 + \beta_{eff} t_c$, where β_{eff} is the effective chirp rate.

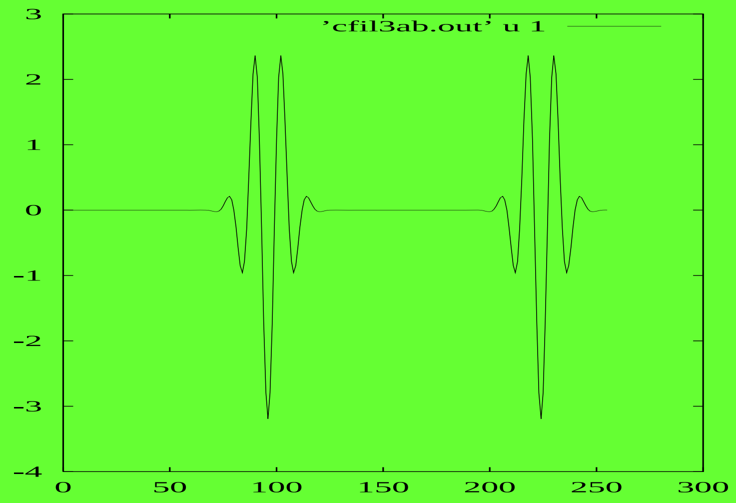


Figure 1: Time domain plot of 2 chirps on same time-frequency line

Separation of Chirps on Same Time-Frequency Line

The Fourier extension image for this signal is shown in the figure below.

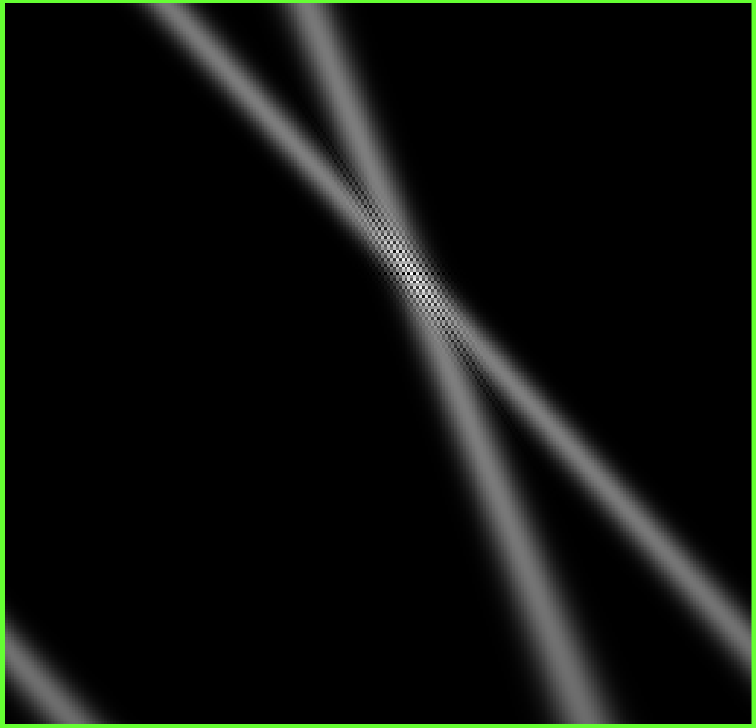
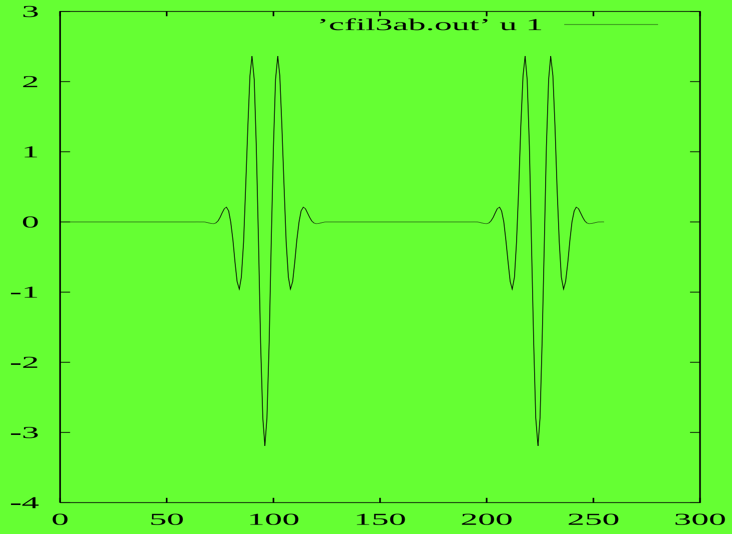


Figure 1: Fourier Extension Image of 2 chirps on same time-frequency line

Separation of Chirps on Same Time-Frequency Line

If the chirps have zero rate (sinusoids) this allows us to detect the fact that we have two sinusoids at different times in our signal. This cannot be done with the normal Fourier Transform. The example shows two sinusoid pulses each of frequency 5Hz and occupying time slots 1 to 2 seconds and 3 to 4 seconds. At the zero effective rate which is also the true zero rate in this case, the two occupy the same point. We note two lines for the two pulses, the slopes of the lines being related to the centre times of the pulses.



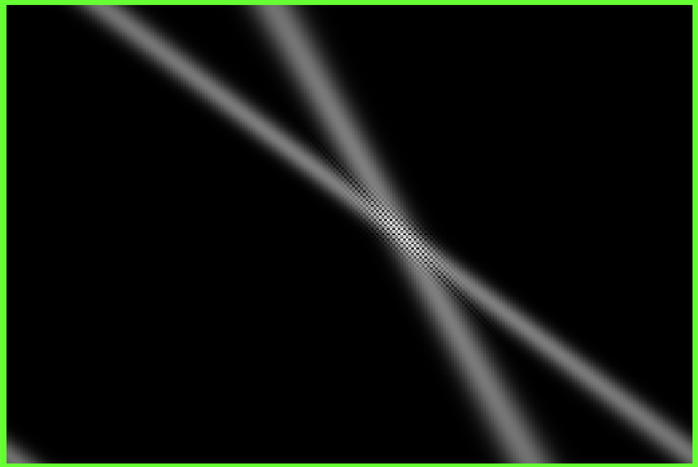
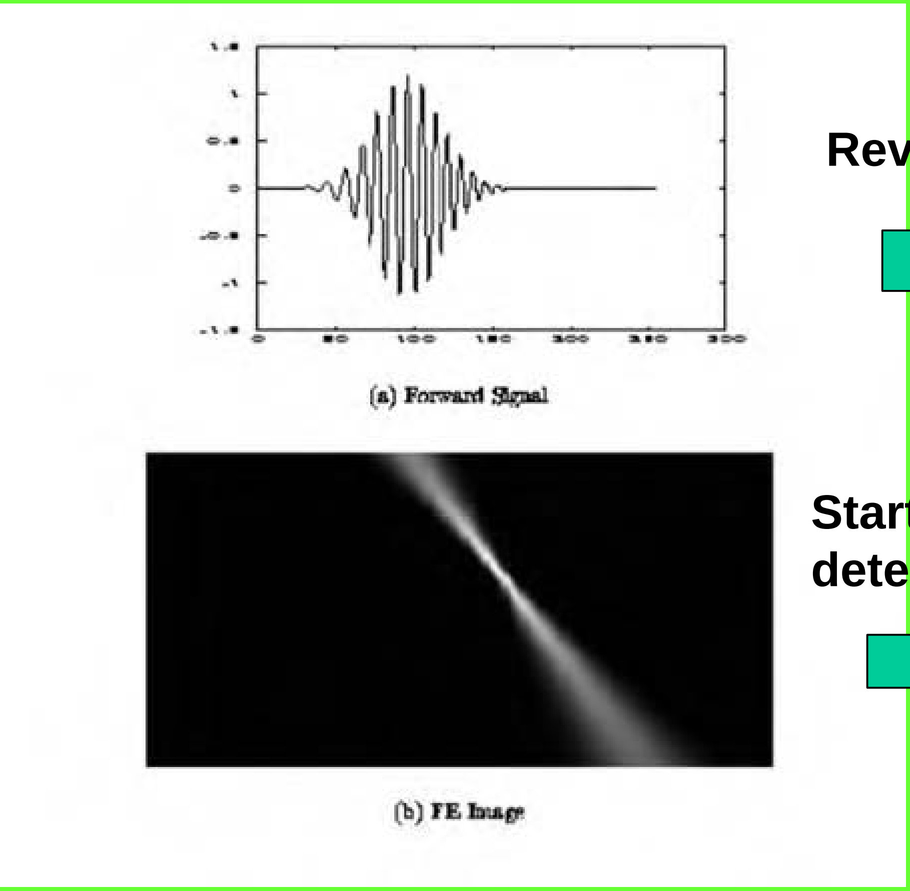


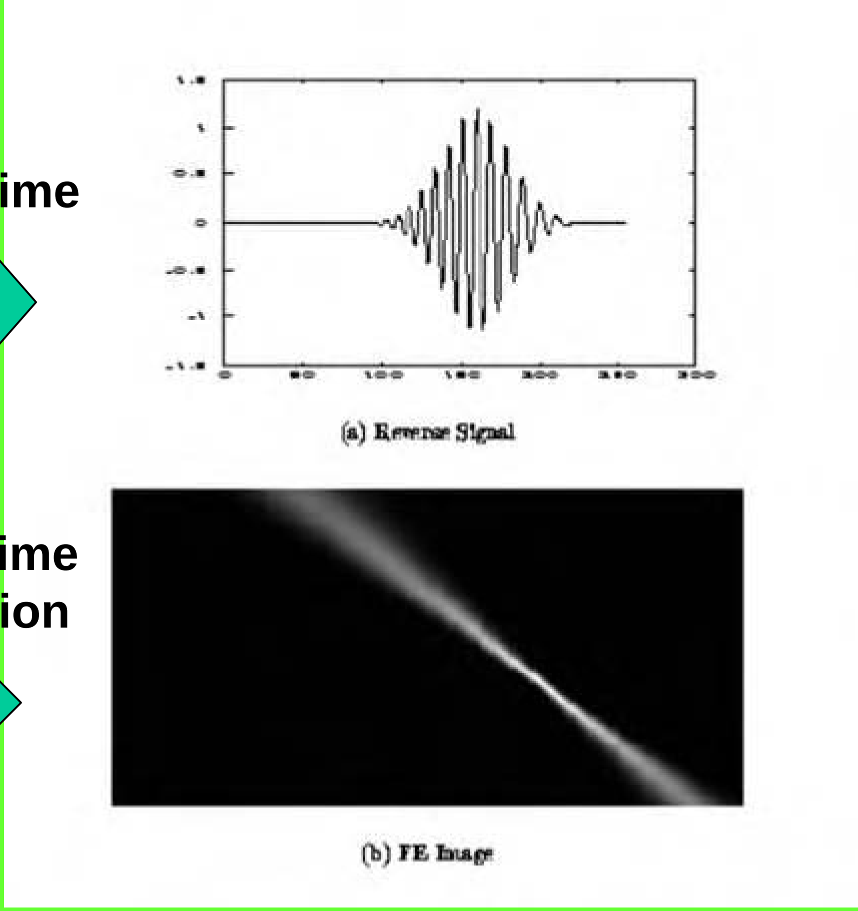
Figure 1: Two sinusoids occupying the same time/frequency line (left) and the Fourier Extension Image (right).

Time Reversal Analysis



Reverse Time

Start/End time determination



Time-Frequency Representation from FE Analysis

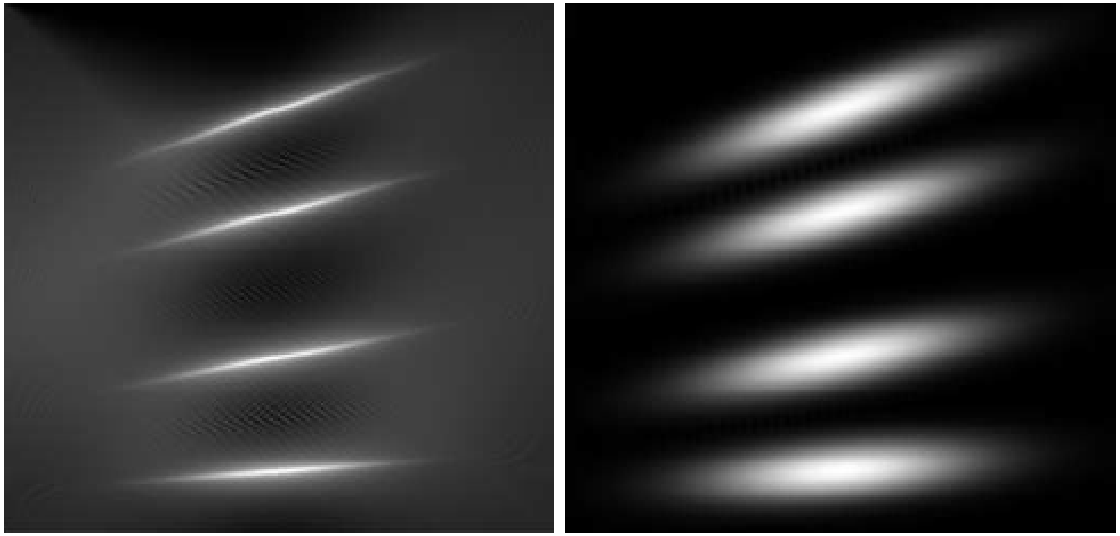


Figure 8: Time-Frequency plots: Hough transform Image(left), Spectrogram(right)

Using Linear Chirps to look at Quadratic Chirps

We could extend the analysis to finding quadratic chirps directly. At this stage let us first examine the effect of analysing a quadratic chirp (or a mixture) using linear chirps.

The chirp represented by the equation

$$f(t) = e^{j(\frac{a}{3}t^3 + ct)}$$

Note that we have avoided the second order term (the skewing term) so that we still only specify a start and end frequency and at time t=0, f=c. In this example, T=4, N=256, f_1=3, f_2=18, t_1=0, t_2=4.

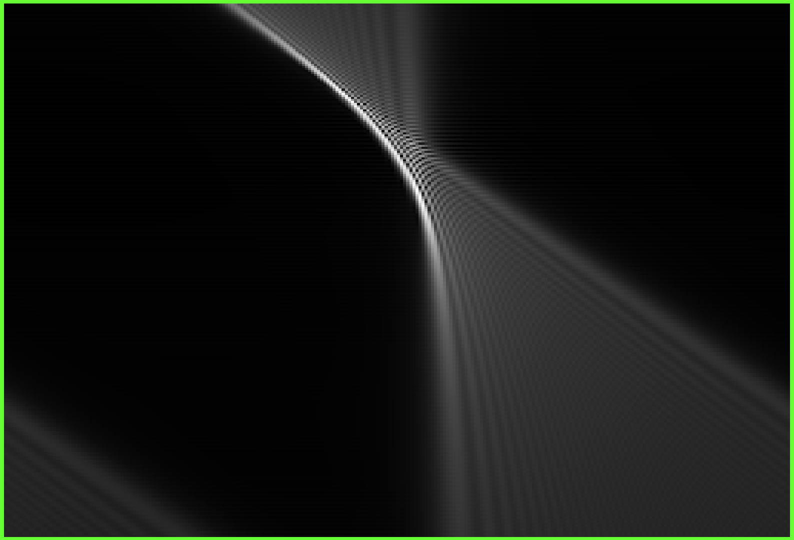
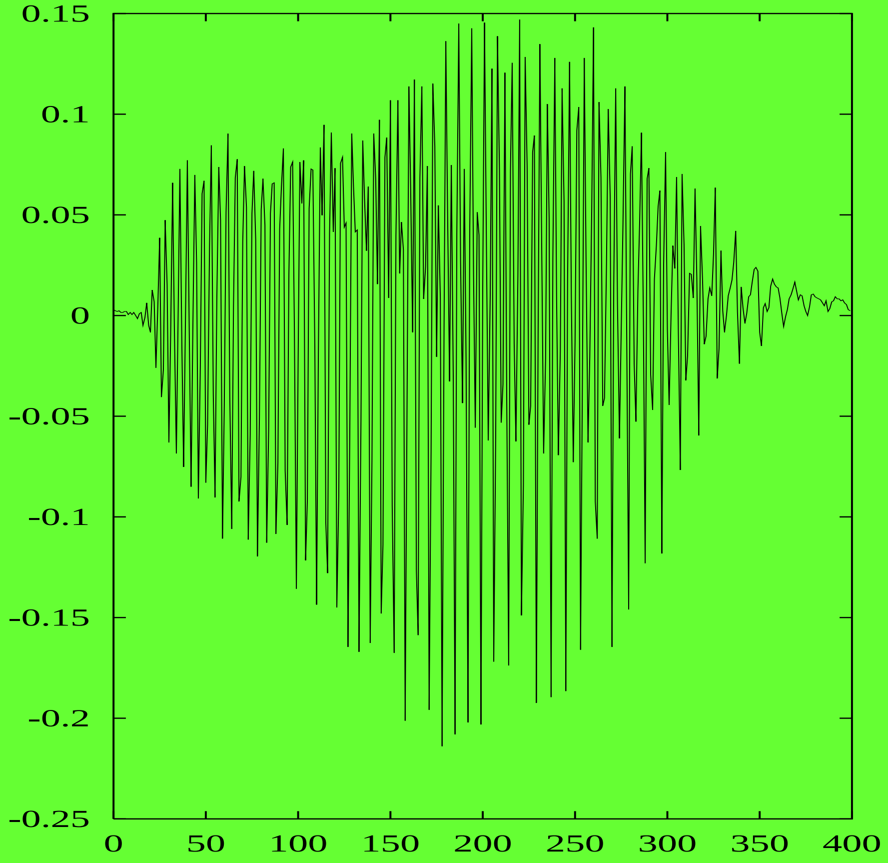
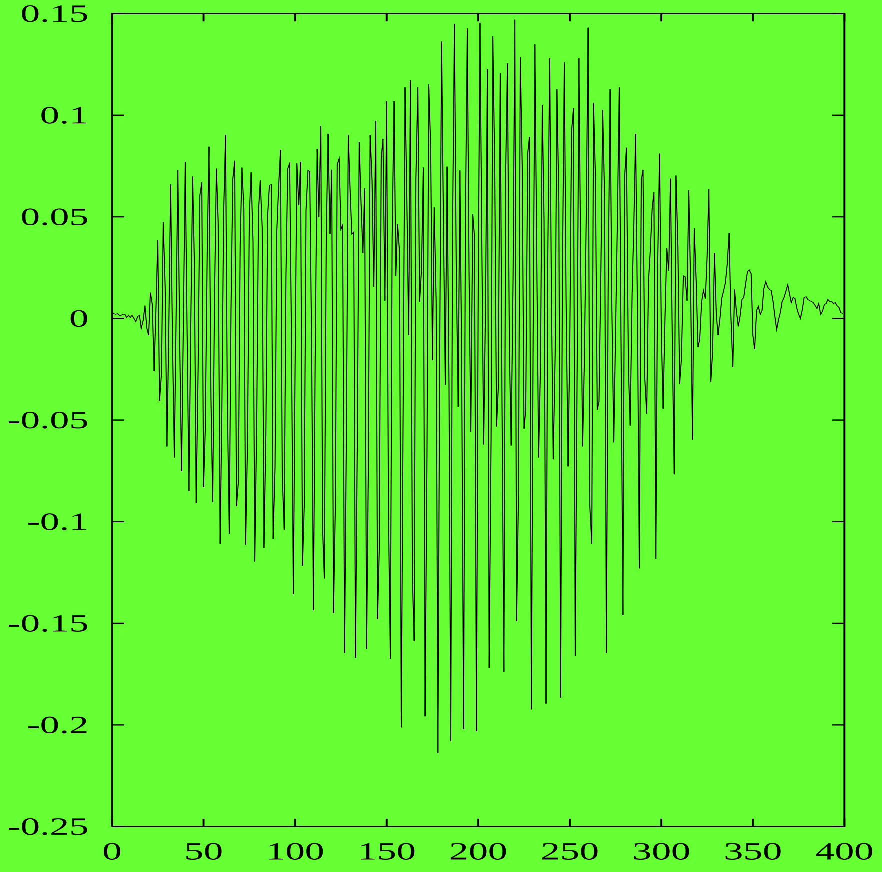


Figure 1: Fourier Extension Image of Quadratic Chirp using Linear Analysing Chirps

Chirp Filtering – The Bat Signal

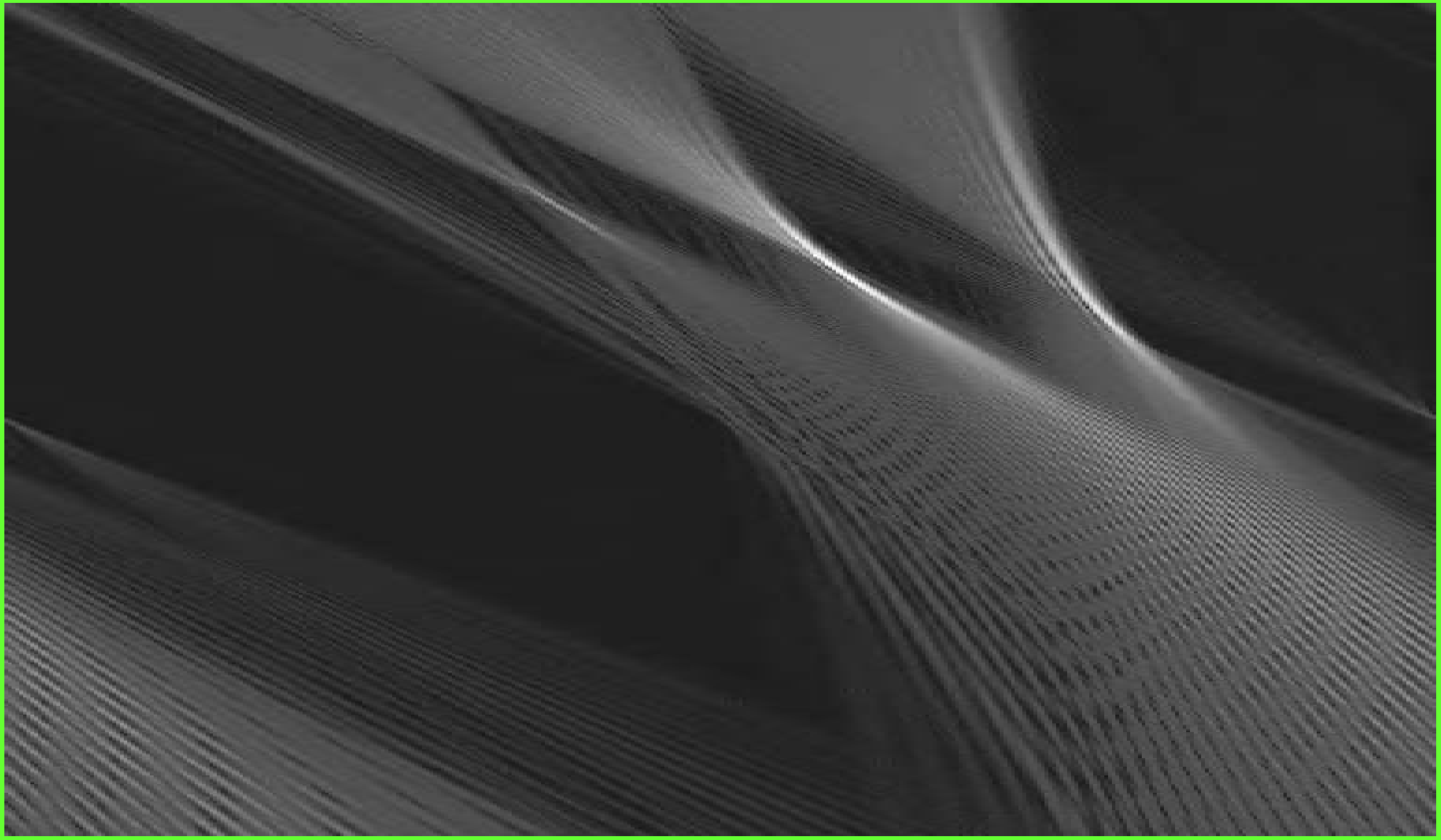


(a) Original Bat Signal

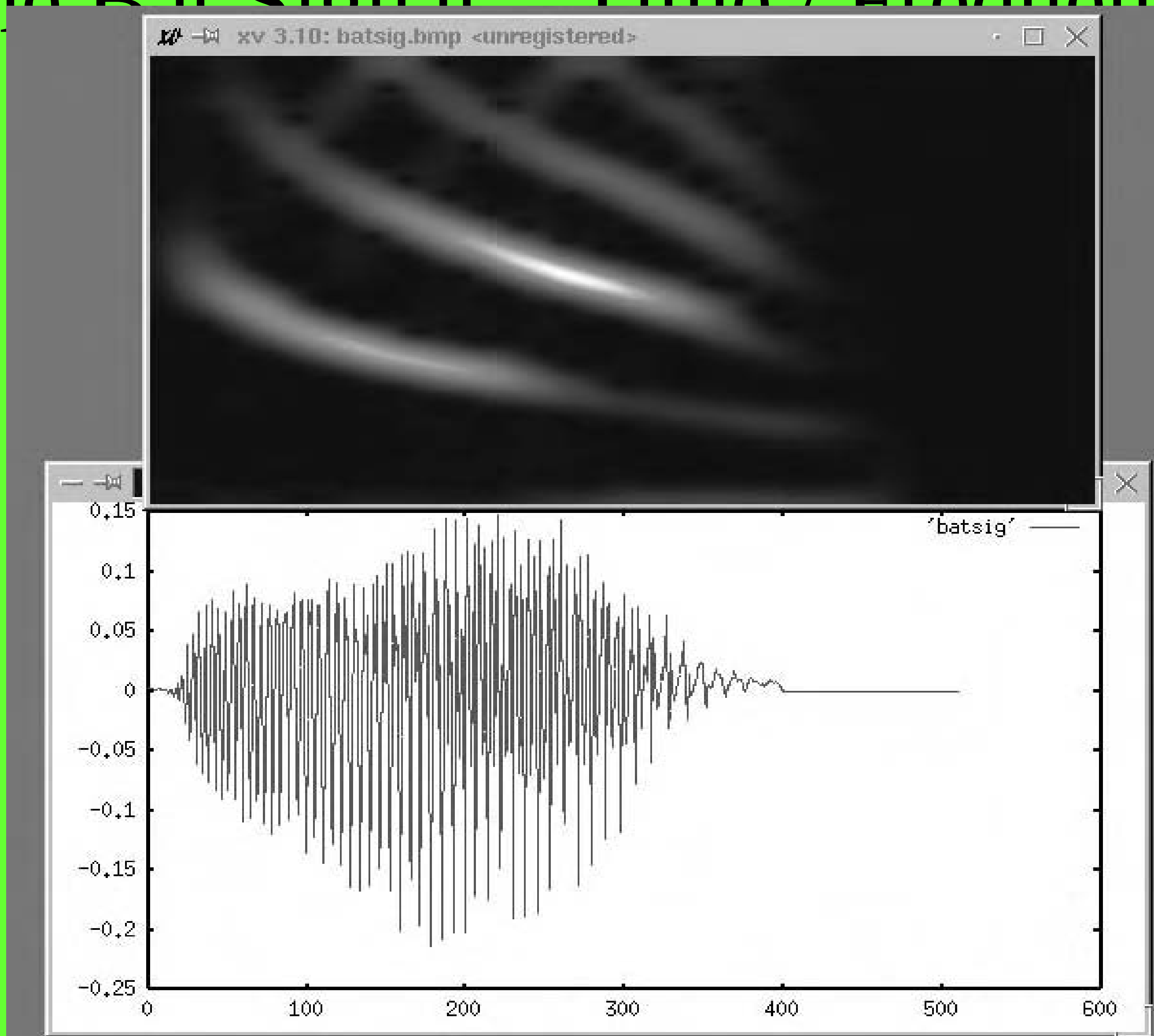


(b) Recovered Bat Signal

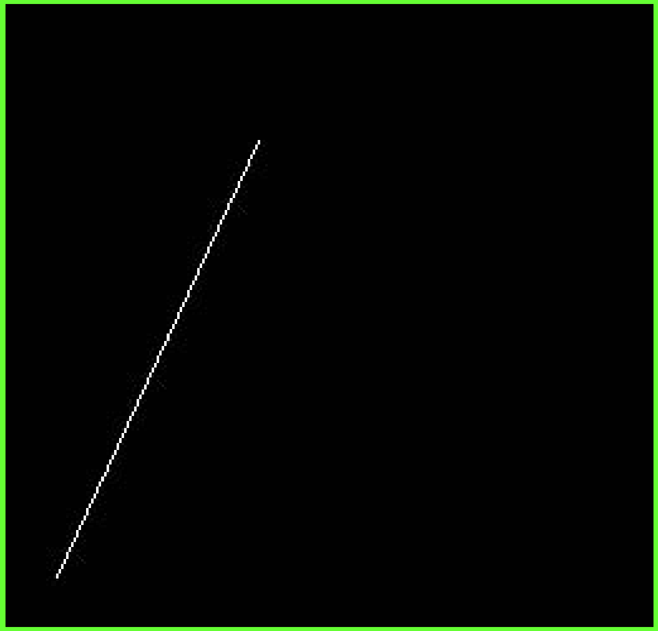
The Bat Signal – Fourier Extension Image



The Bat Signal – Time / Frequency



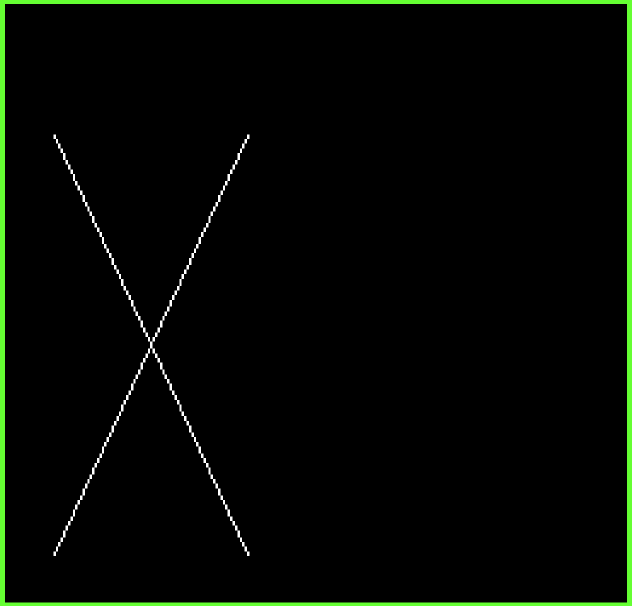
The Hough Transform



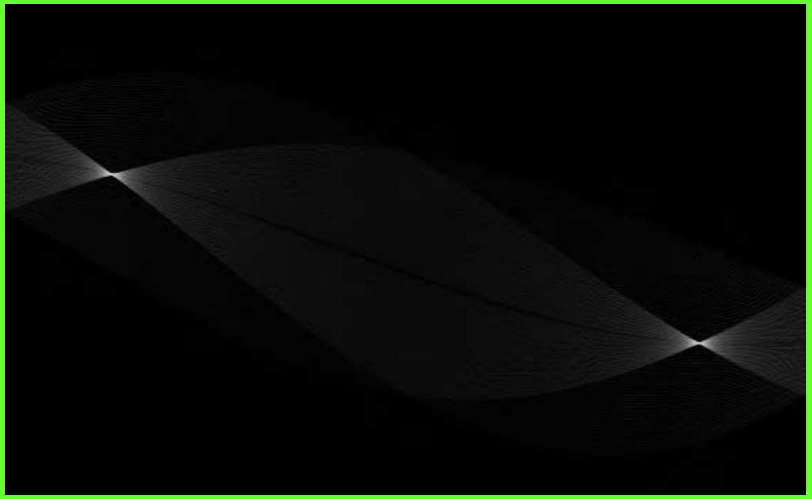
(a) An image with a line in it

(b) The Hough Transform of the Image.

The Hough Transform

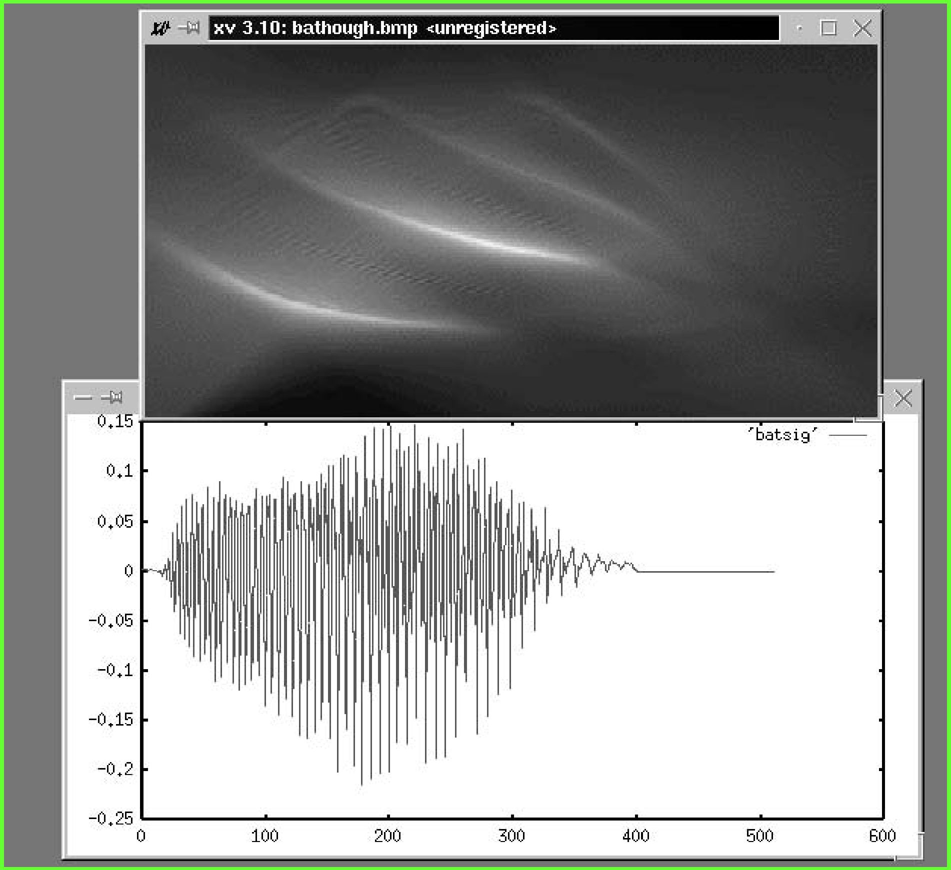


(a) An image with two lines in it

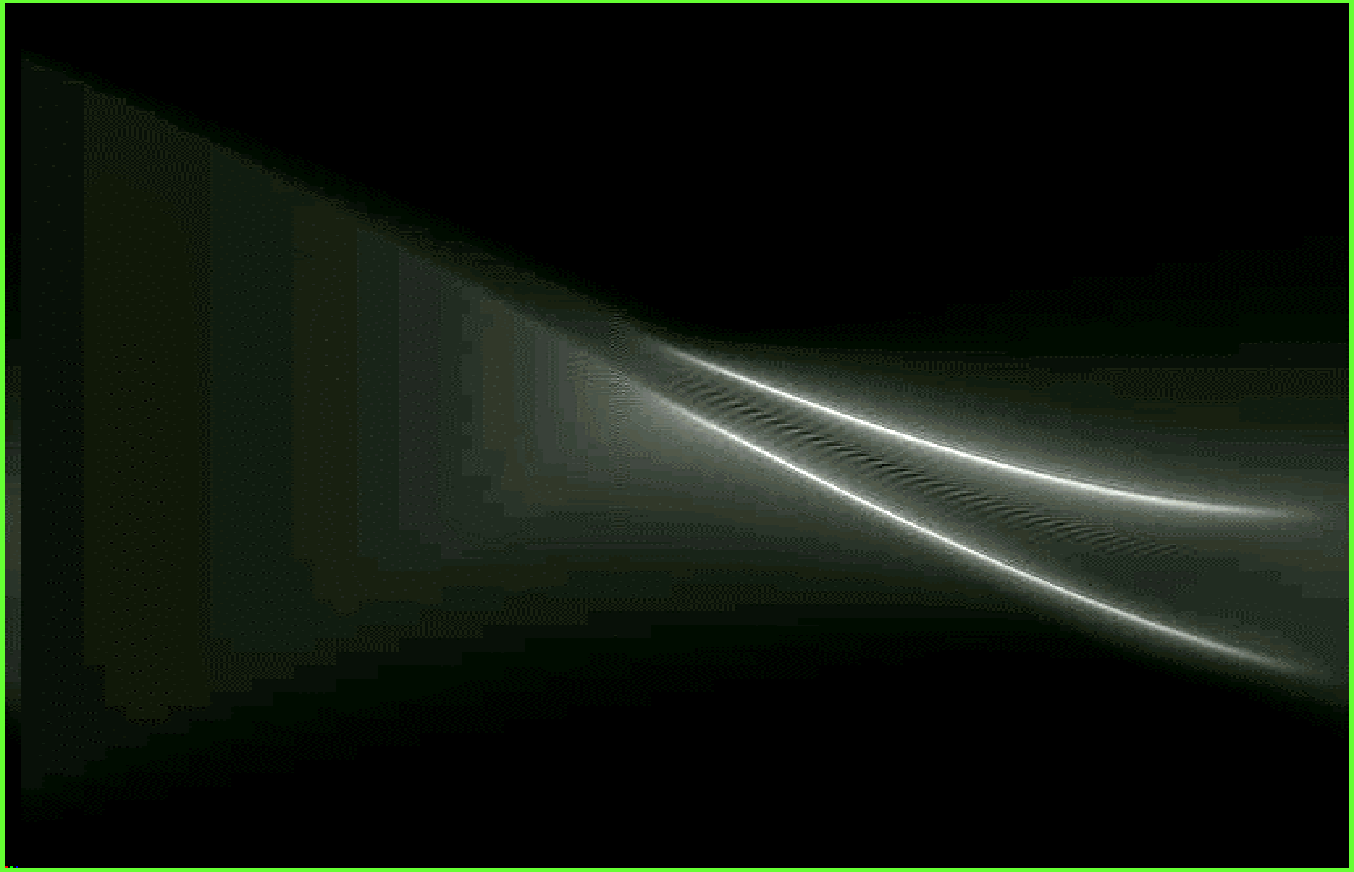


(b) The Hough Transform of the Image.

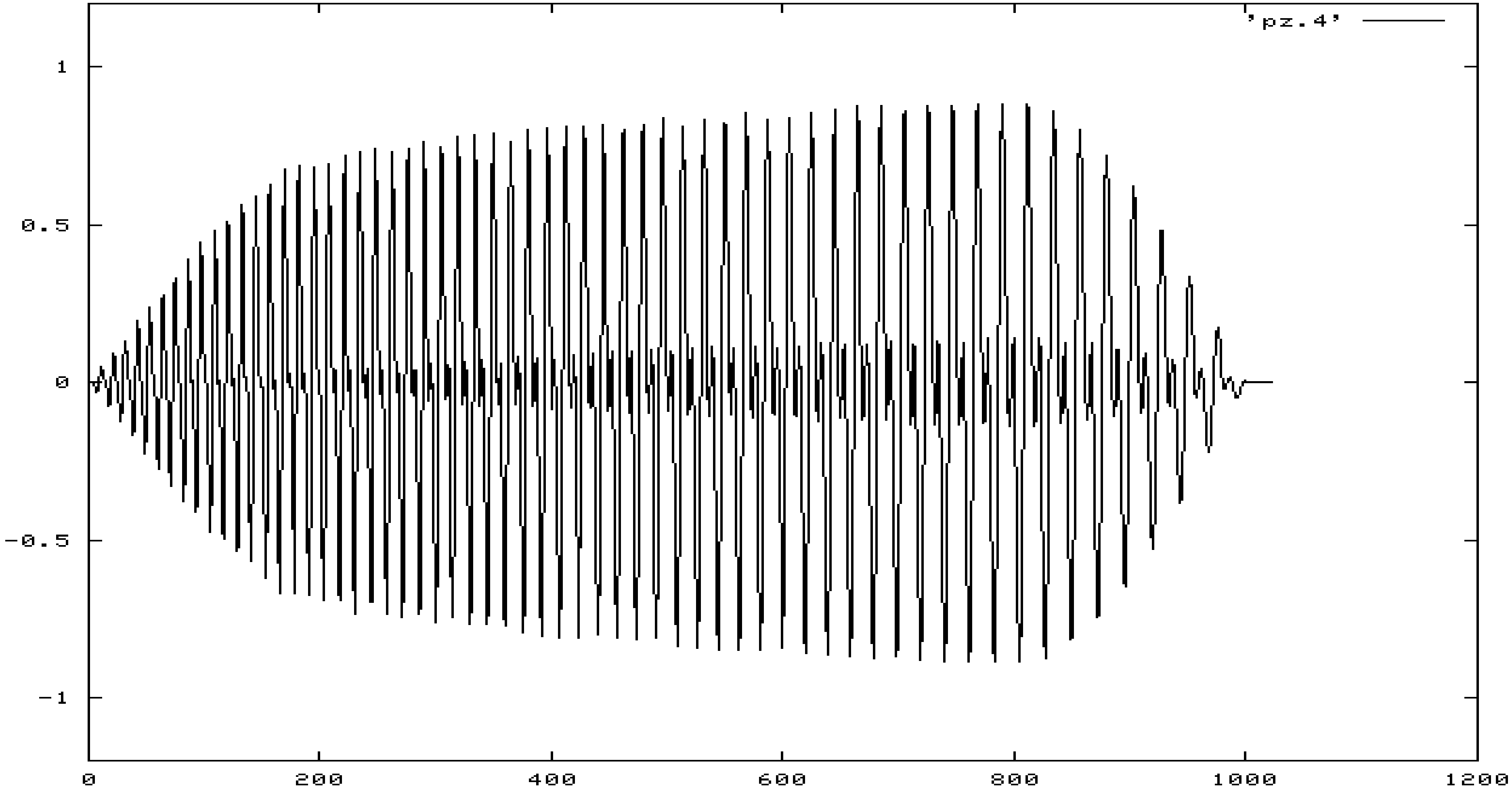
The Bat Signal – Hough Space



Time Frequency Sequence of Bat Sonar

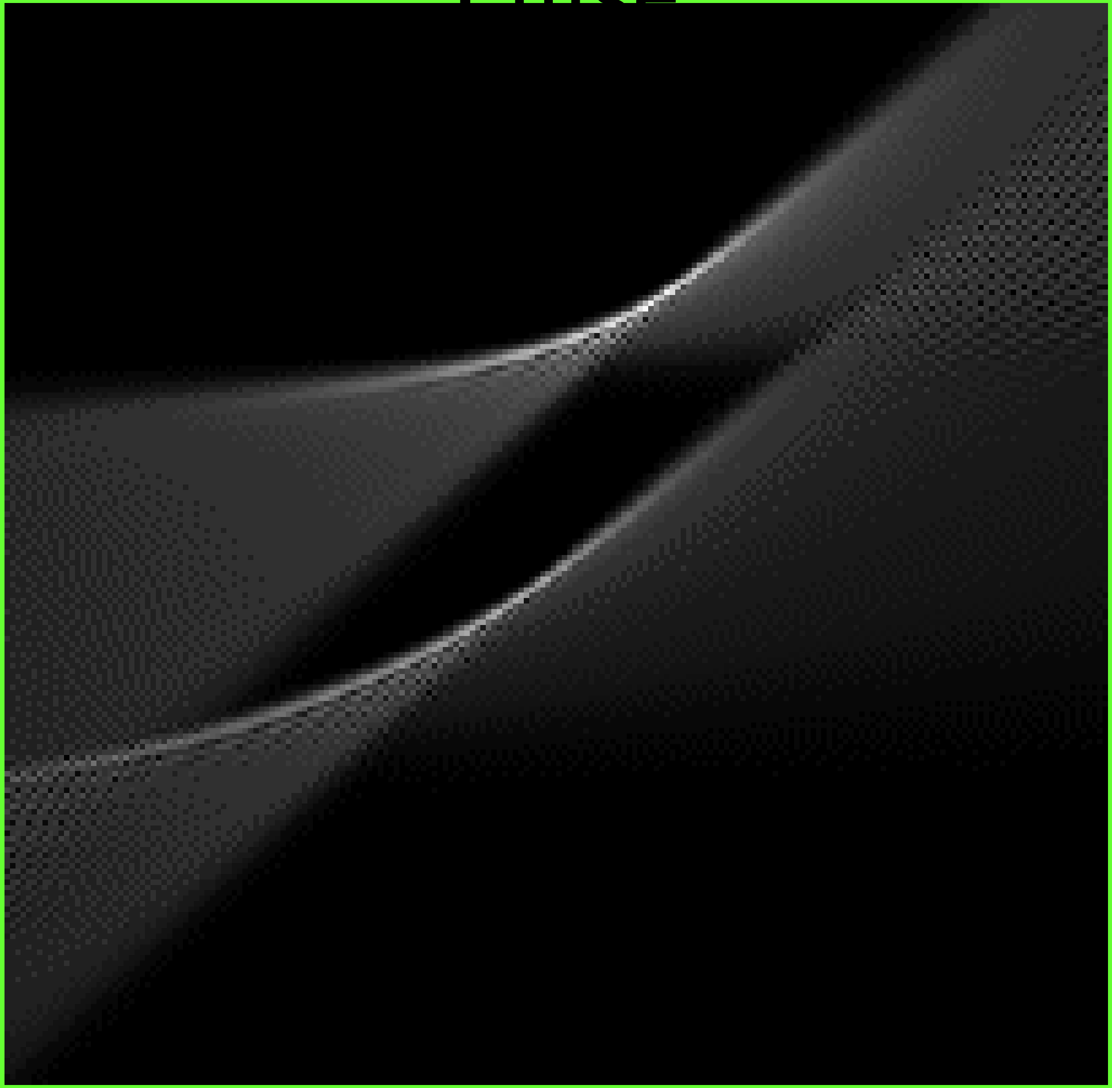


Single Bat Pulse

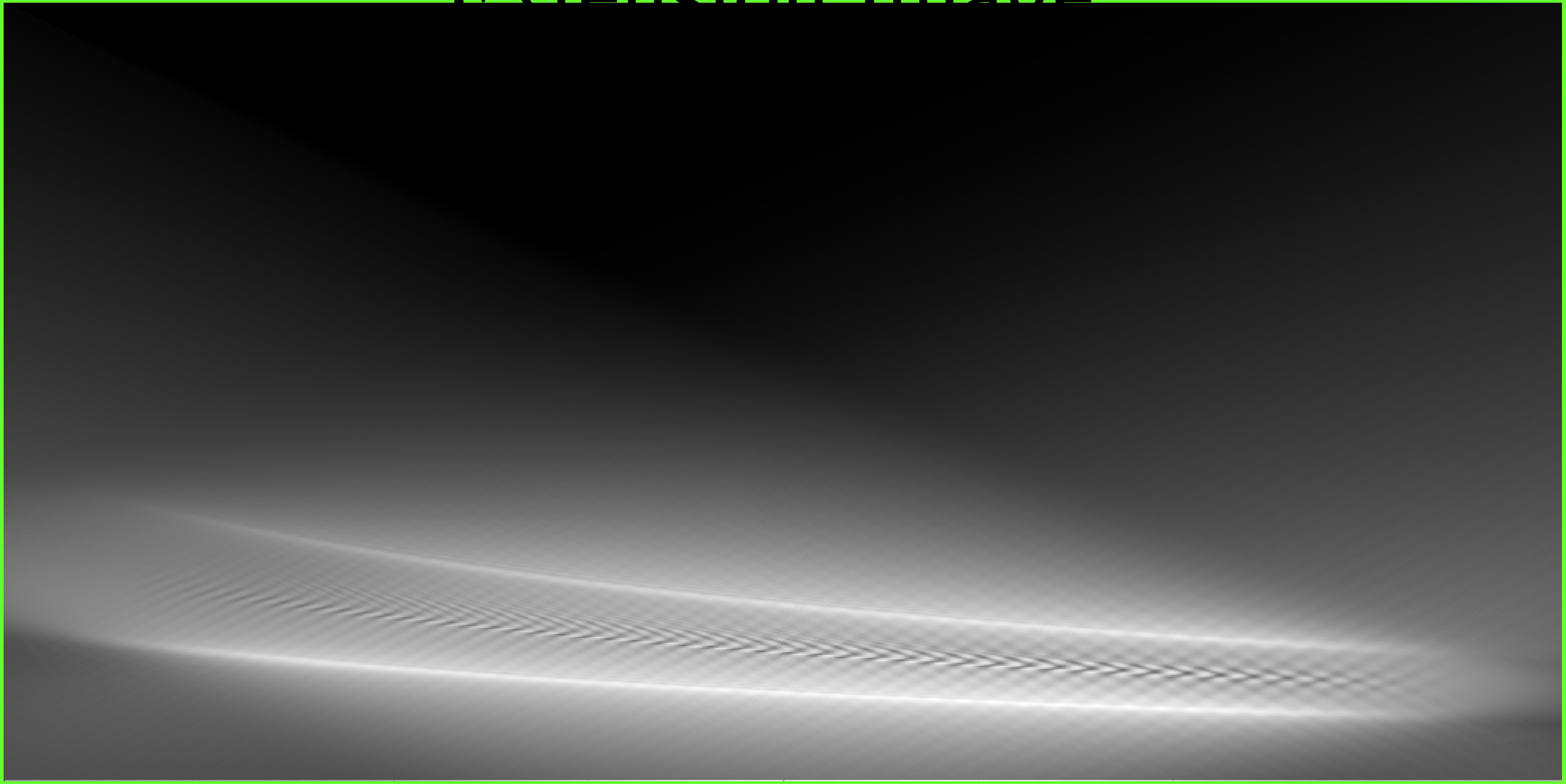


Amplitude time samples for a single simulated bat pulse.

Fourier Extension Image of Bat Pulse

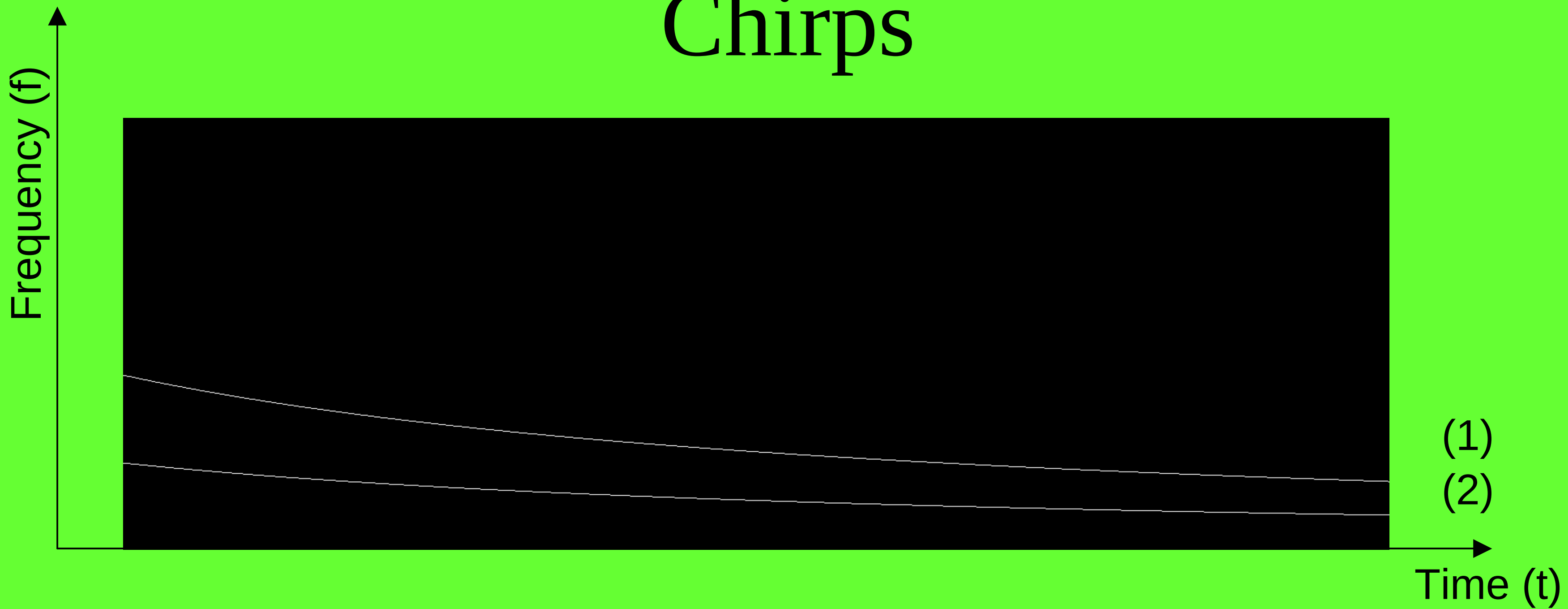


Hough Transform of Fourier Extension Image



This image is effectively the time frequency plot of the bat pulse.

Time Frequency Plot of Estimated Chirps

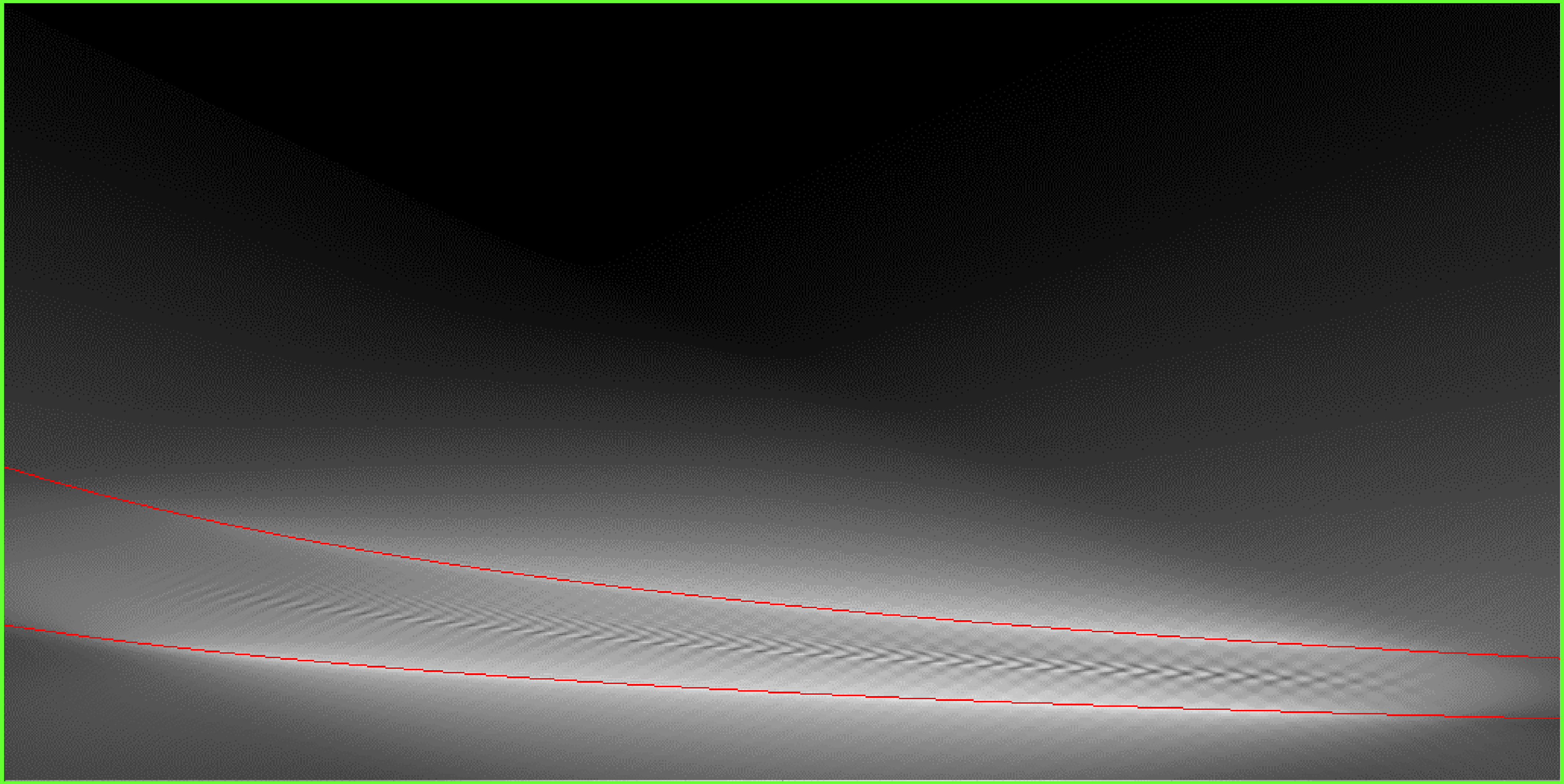


Chirp parameters for fit to $$f = \frac{1}{a + bt}$$

(1) a=4.856310e-03, b=7.472294e-06

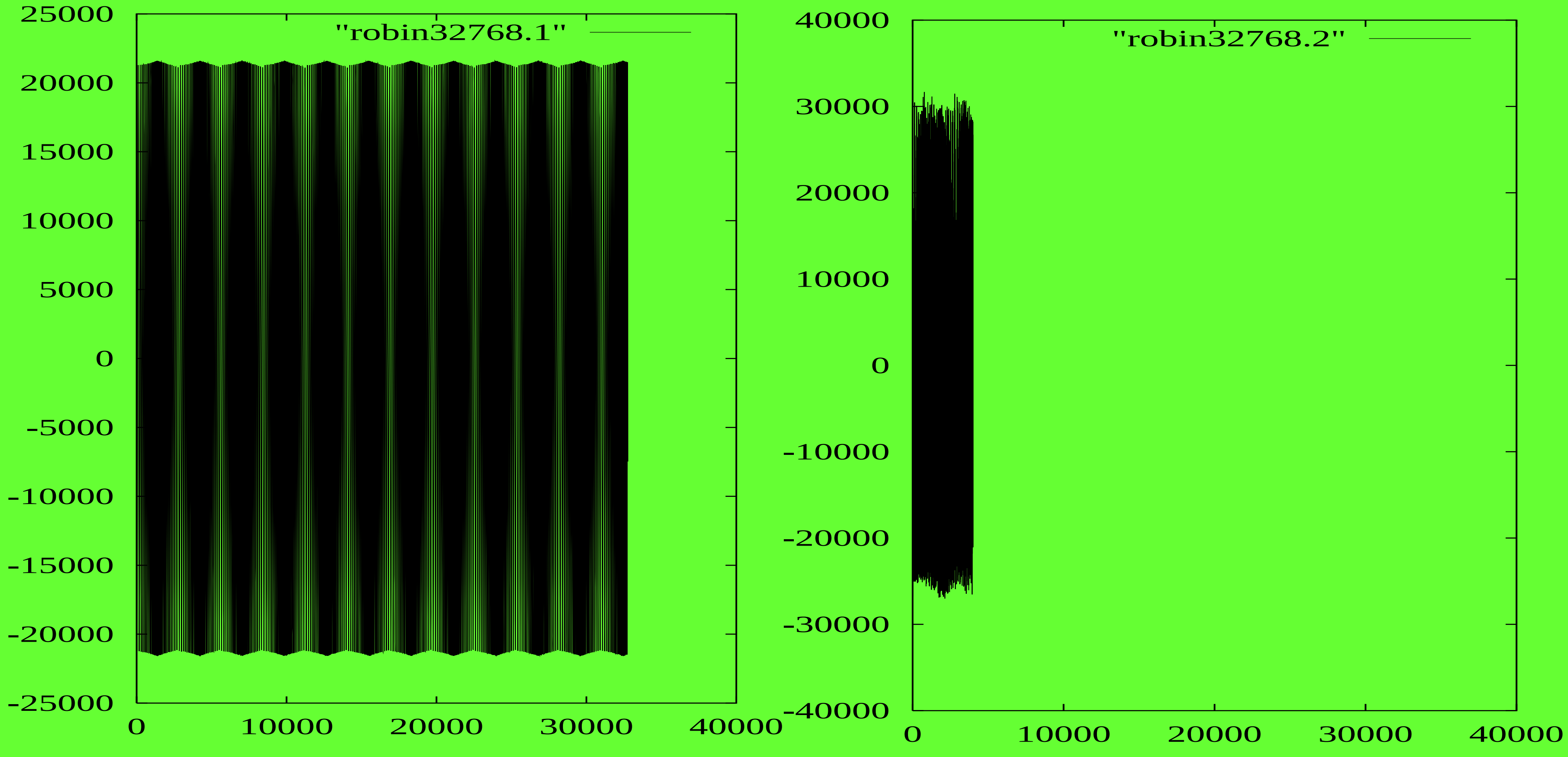
(2) a=9.815784e-03, b=1.477589e-05

Estimated Chirps



Time Frequency Image with estimated chirps overlaid in red.

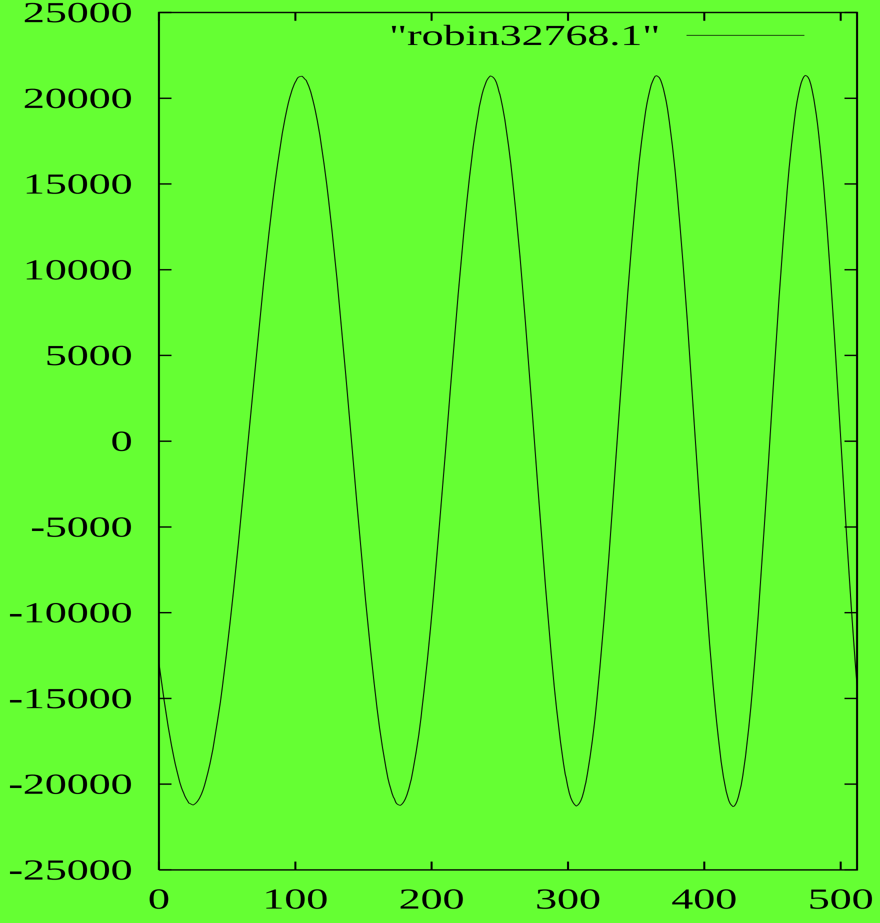
Through Water EM Transmission



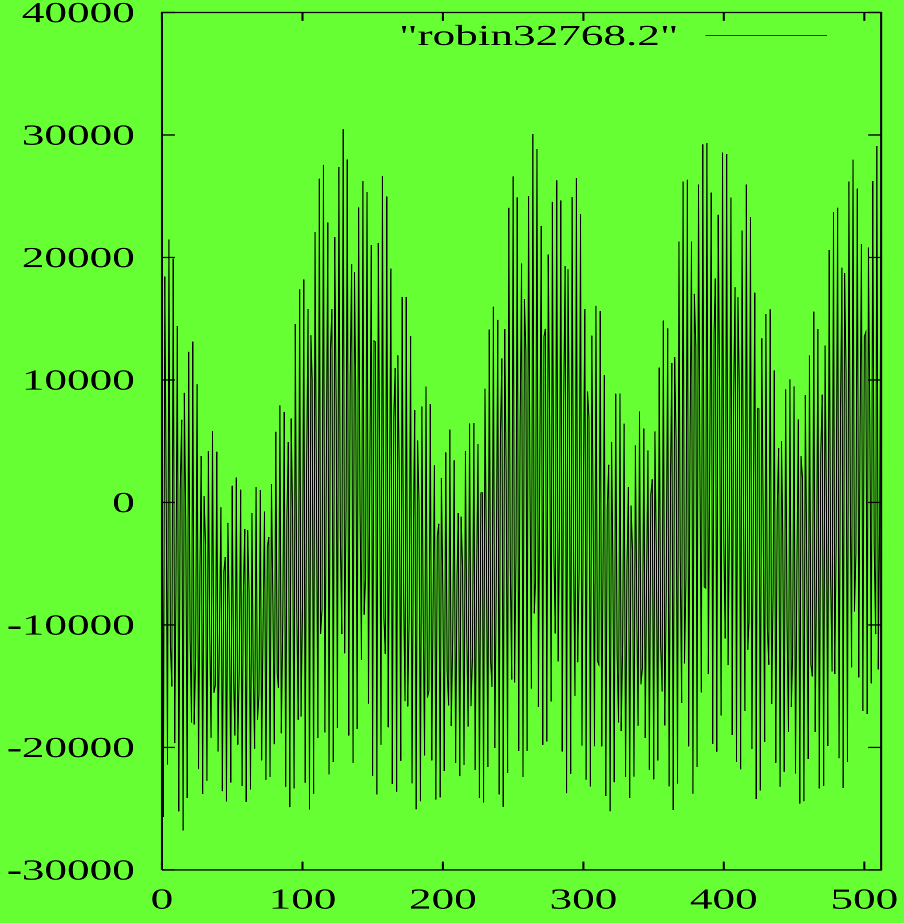
(a) Transmitted Chirp

(b) Received Chirp

Through Water EM Transmission



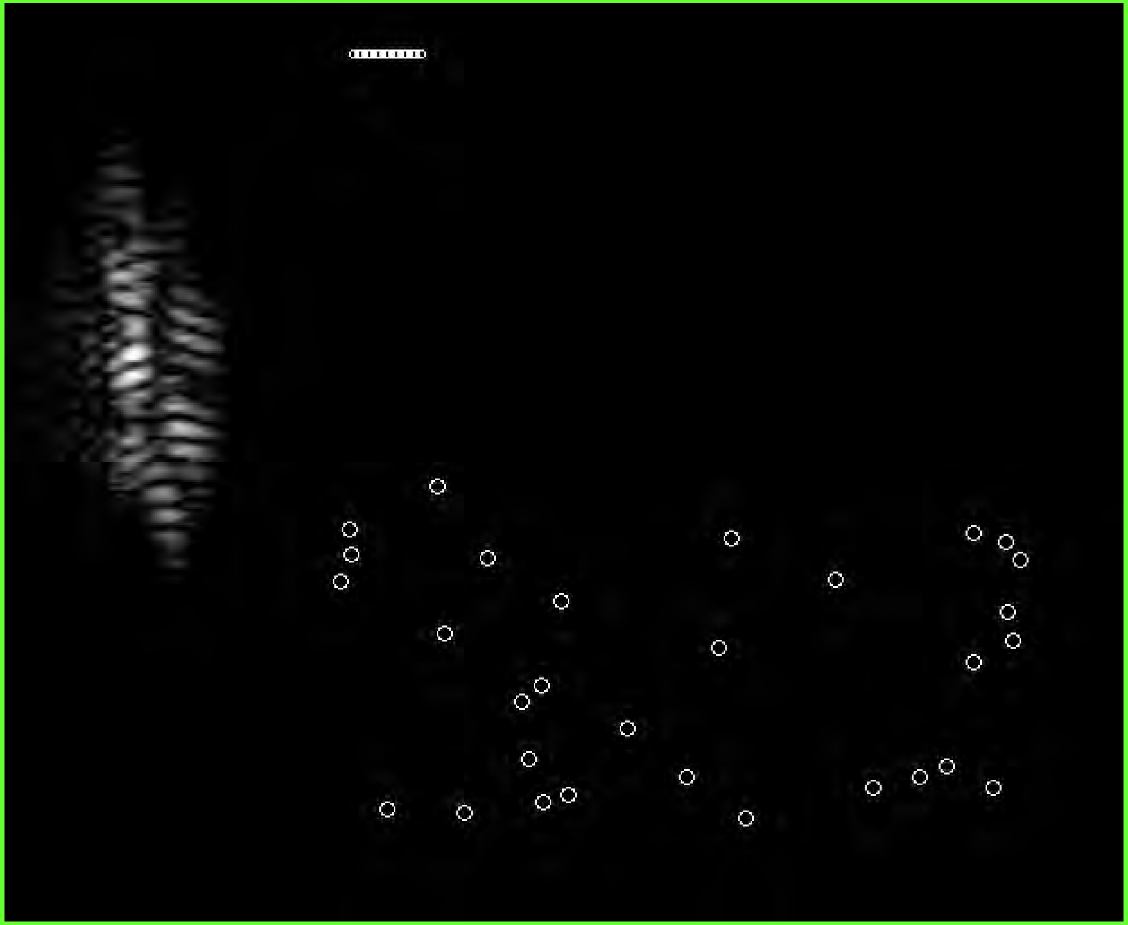
(a) Transmitted Chirp zoomed portion



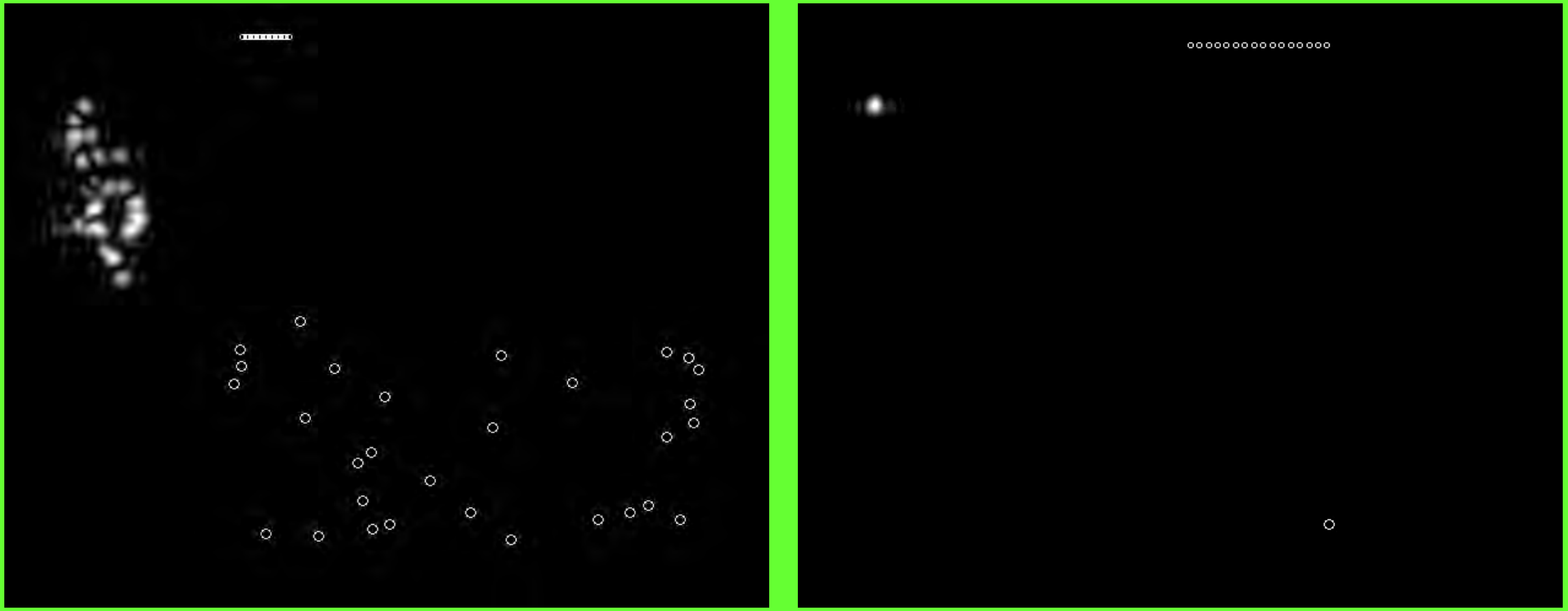
(b) Received Chirp zoomed portion

Through Water EM Transmission

Beam Forming with a Sinusoid



Beam Forming with a Chirp



FORTKEY LTD

Appendix 3f

Laurie Linnett

Linear Chirp

Quadratic phase:

$$\exp\{ j[(a/2)(t-t_1)^2 + b(t-t_1)]\}$$

$$= \exp\{ j[(a/2)t^2 - att_1 + (a/2)t_1^2 + bt - bt_1]\}$$

Linear Chirp

We remove the Quadratic phase by multiplying by

$$\exp\{-j(a/2)t^2\}$$

This leaves a residual frequency of

$$(b-at_1)T$$

In the Fourier Extension domain the coordinates are

$$\{(b-at_1)T,\, aT^2\}$$

Fourier Extensions for Practical Chirp Analysis

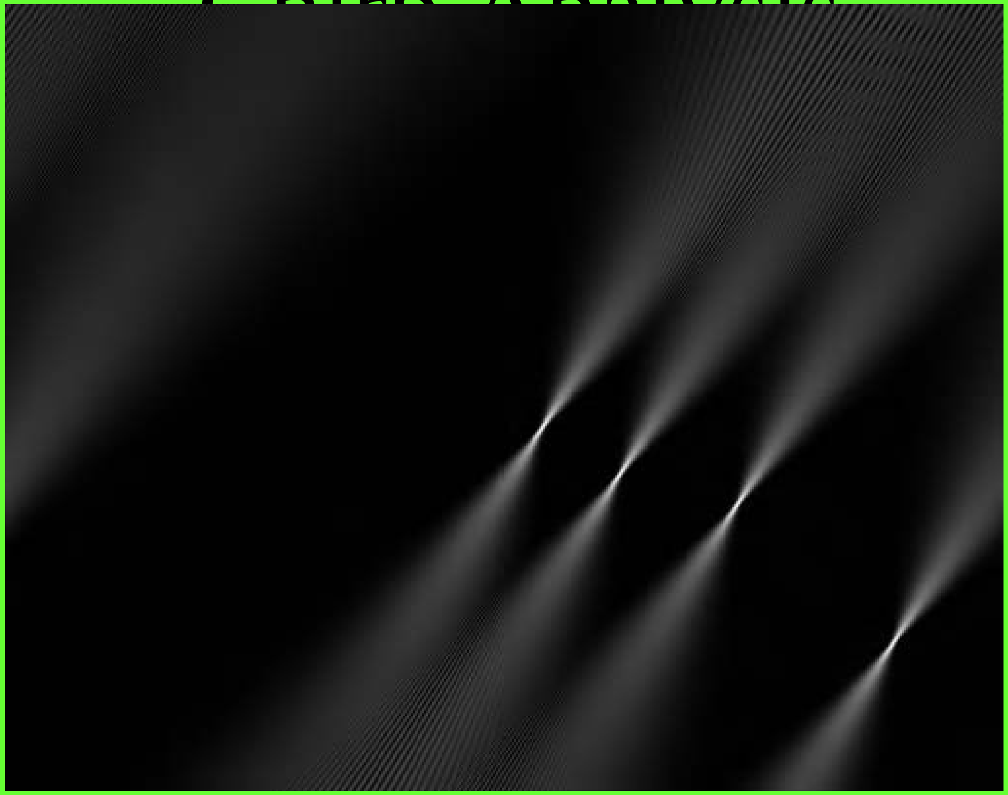
- To illustrate the algorithm, the following four chirps given in the table were constructed and analysed to produce the magnitude image shown in the figure.

amplitude	t_1	t_2	f_1	f_2
100.0	0.0	2.0	10.0	20.0
100.0	0.0	2.0	30.0	55.0
100.0	0.0	2.0	60.0	95.0
100.0	0.0	2.0	100.0	180.0

Chirp parameters used in Fourier Extension Algorithm Example

- The total sample time was $T=2.0$ seconds and $N=512$, a Gaussian envelope was used in the signals.

Fourier Extensions for Practical Chirp Analysis



Fourier Extension Image

- As can be seen we have 4 distinct highlights in the image. These correspond to the four chirps.

Separation of Chirps on the Same Time-Frequency Line

- To see the effects of this consider the signal shown in the figure below. It is the signal of a chirp occupying the time slot from 1 to 2 seconds and frequencies 5 to 7 Hz and also a chirp occupying the time slot from 3 to 4 seconds and frequencies 9 to 11 Hz. That is both chirps have the same rate and occupy the same residual frequency bin given by $(b-at_1)T=12$. That is at the correct analysing chirp rate, both have rate zero and hence cannot be separated at this point. However, away from the correct analysing chirp the two chirps may be separated. The maximum occurring at $\omega = \omega_0 + \beta_{eff} t_c$, where β_{eff} is the effective chirp rate.

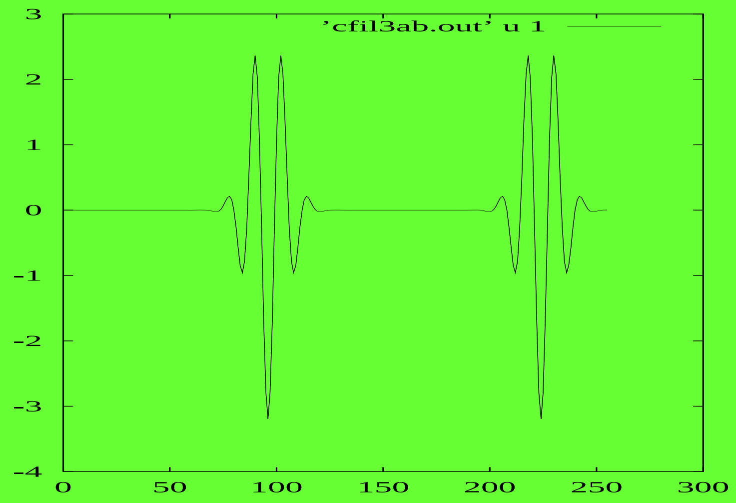


Figure 1: Time domain plot of 2 chirps on same time-frequency line

Separation of Chirps on Same Time-Frequency Line

The Fourier extension image for this signal is shown in the figure below.

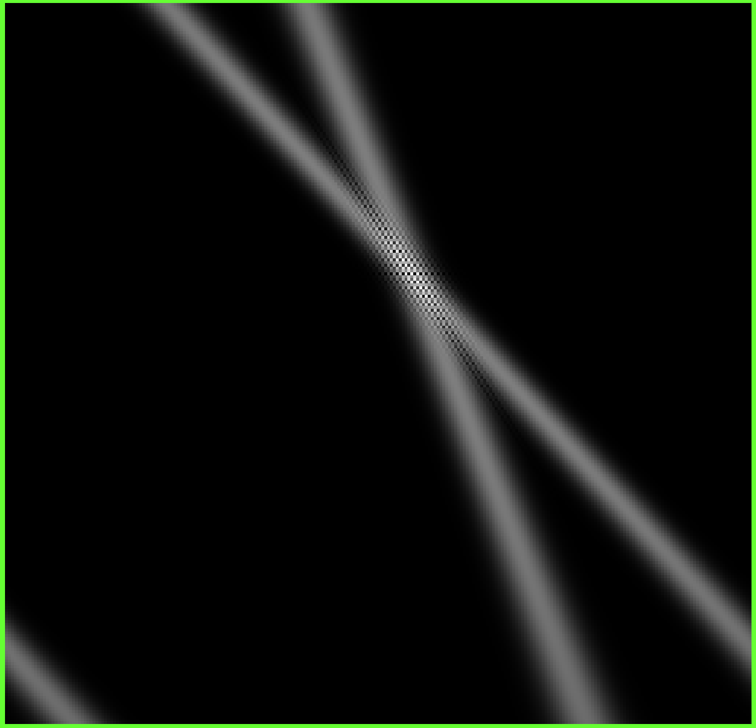
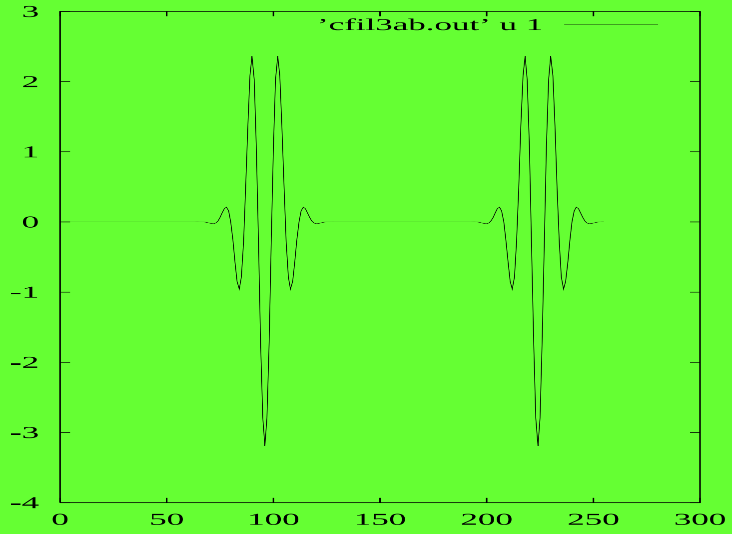


Figure 1: Fourier Extension Image of 2 chirps on same time-frequency line

Separation of Chirps on Same Time-Frequency Line

If the chirps have zero rate (sinusoids) this allows us to detect the fact that we have two sinusoids at different times in our signal. This cannot be done with the normal Fourier Transform. The example shows two sinusoid pulses each of frequency 5Hz and occupying time slots 1 to 2 seconds and 3 to 4 seconds. At the zero effective rate which is also the true zero rate in this case, the two occupy the same point. We note two lines for the two pulses, the slopes of the lines being related to the centre times of the pulses.



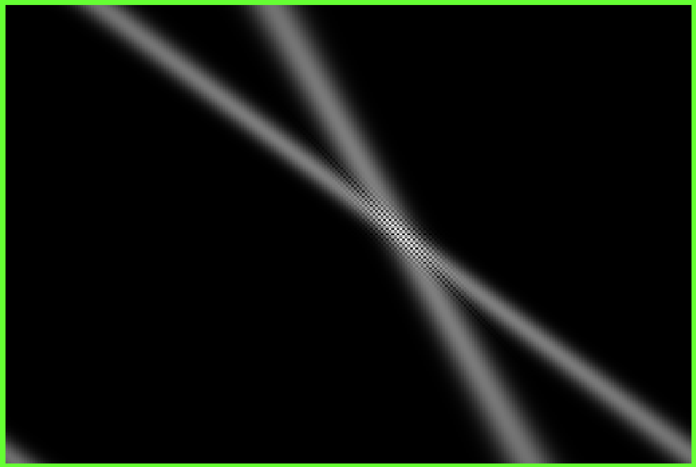
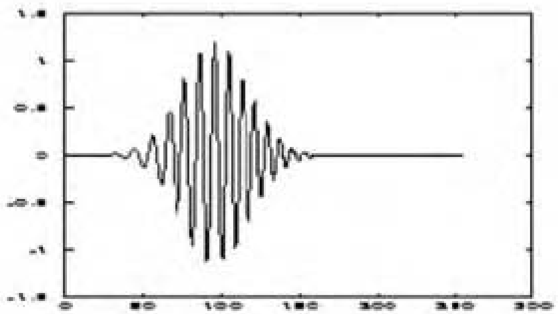


Figure 1: Two sinusoids occupying the same time/frequency line (left) and the Fourier Extension Image (right).

Time Reversal Analysis

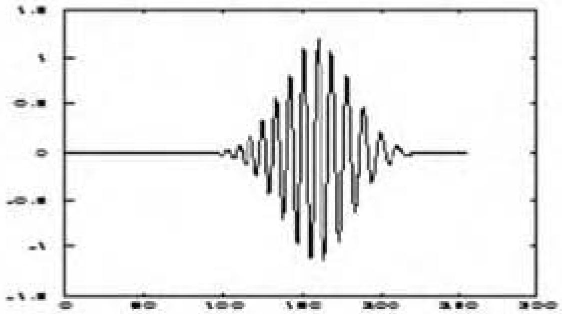


(a) Forward Signal

(b) FE Image

Reverse Time

Start/End time determination



(a) Reverse Signal

(b) FE Image

Time-Frequency Representation from FE Analysis

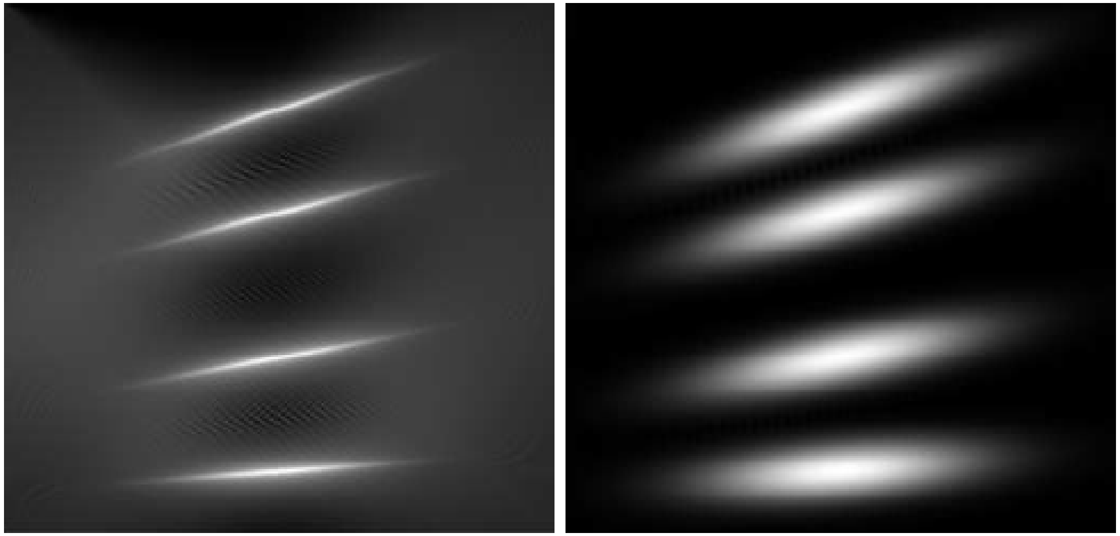
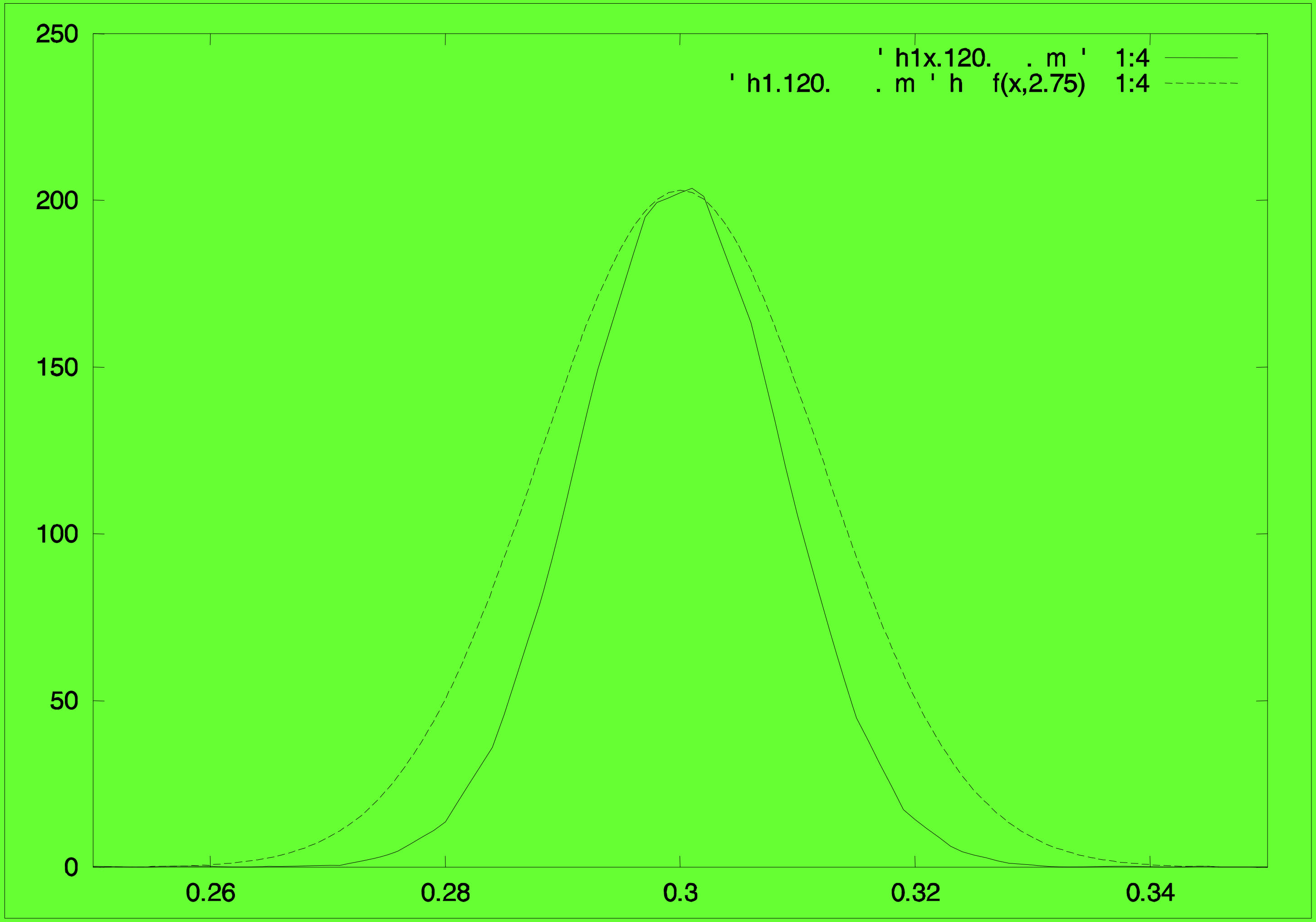


Figure 8: Time-Frequency plots: Hough transform Image(left), Spectrogram(right)

ACF and FE



250
200
150
100
50
0
0.26
0.28
0.3
0.32
0.34
' h1x.120. . m ' 1:4
' h1.120. . m ' h f(x,2.75) 1:4

Quadratic Chirp

Cubic phase:

$$\exp\{j[(a/3)(t-t_1)^3+b(t-t_1)]\}$$

$$=(a/3)t^3-at^2t_1+att_1^2-(a/3)t_1^3+bt-bt_1$$

Quadratic Chirp

We remove the Cubic phase by multiplying by

$$\exp\{-j(a/3)t^3\}$$

This leaves a Linear chirp (quadratic phase)

$$= -at^2 t_1 + att_1^2 - (a/3)t_1^3 + bt - bt_1$$

The Linear phase is then removed to give a residual frequency of

$$(b + at_1^2)T$$

In the Fourier Extension domain the coordinates are

$$\{(b + at_1^2)T, -2at_1T^2\}$$

FE Quadratic Chirp

Cubic Chirp

Quartic phase:

$$\exp\{j[(a/4)(t-t_1)^4 + b(t-t_1)]\}$$

$$= (a/4)t^4 - at^3t_1 + 6(a/4)t^2t_1^2 - att_1^3 + (a/4)t_1^4 + bt - bt_1$$

Cubic Chirp

We remove the quartic phase by multiplying by

$$\exp\{-j(a/4)t^4\}$$

This leaves a quadratic chirp (cubic phase)

$$= -at^3t_1 + 6(a/4)t^2t_1^2 - att_1^3 + (a/4)t_1^4 + bt - bt_1$$

The cubic phase is then removed by multiplying by

$$\exp\{jat_1t^3\}$$

This leaves a quadratic phase, which is removed by multiplying by

$$\exp\{-j6(a/4)t_1^2t^2\}$$

Cubic Chirp

We are left with a residual frequency of

$$(b - at_1^3)T$$

In the Fourier Extension domain the coordinates are

$$\{(b - at_1^3)T,\ 3at_1^2T^2\}$$

Appendix 3g

Gordon Hayward

New Technologies for Ultra Wideband Ultrasonic Transducers

G. Hayward

Centre for Ultrasonic Engineering University of Strathclyde

Contents

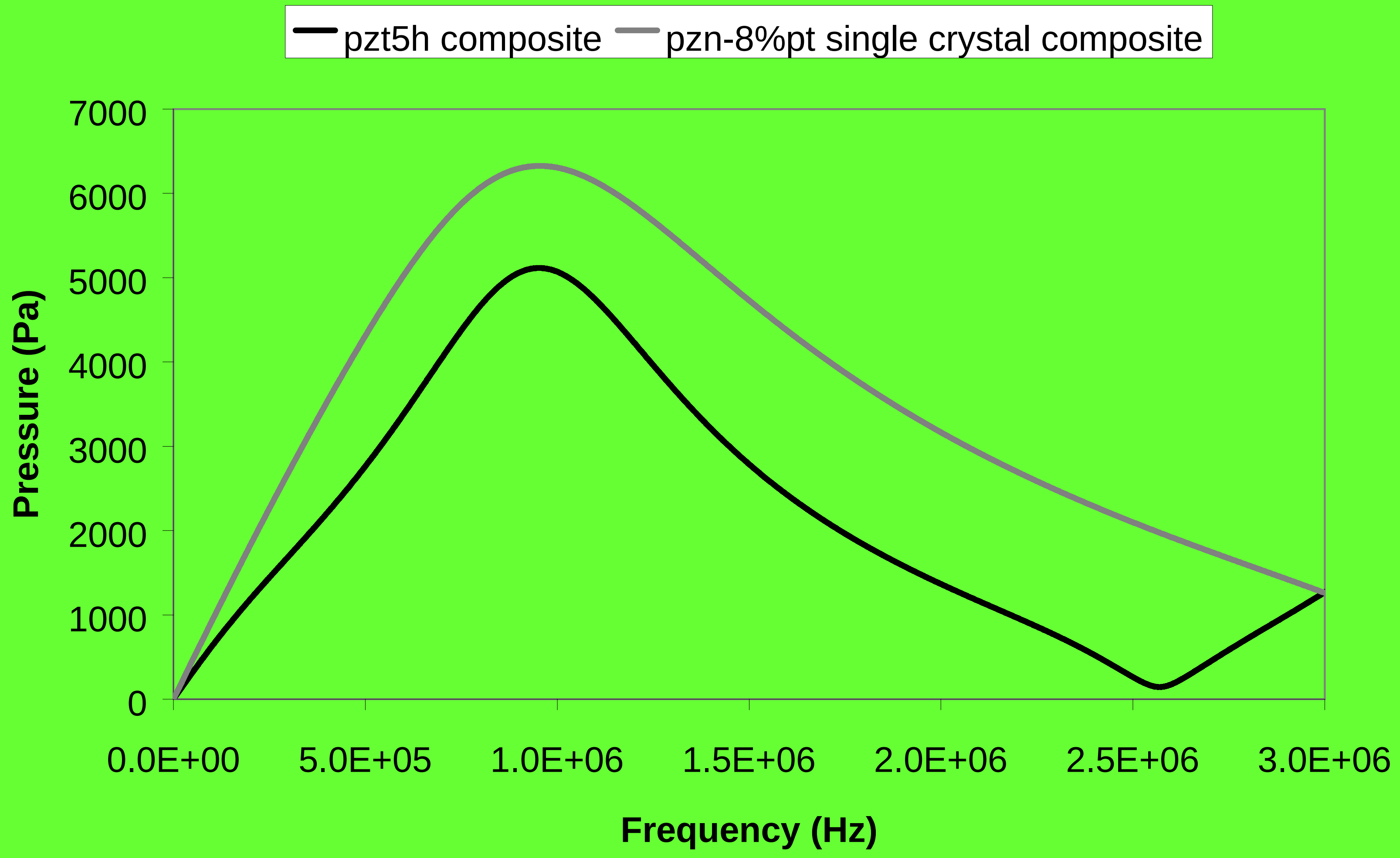
- Single crystal materials
- Multi-layered composites
- Inversion layer transducers

Perovskite Single Crystals

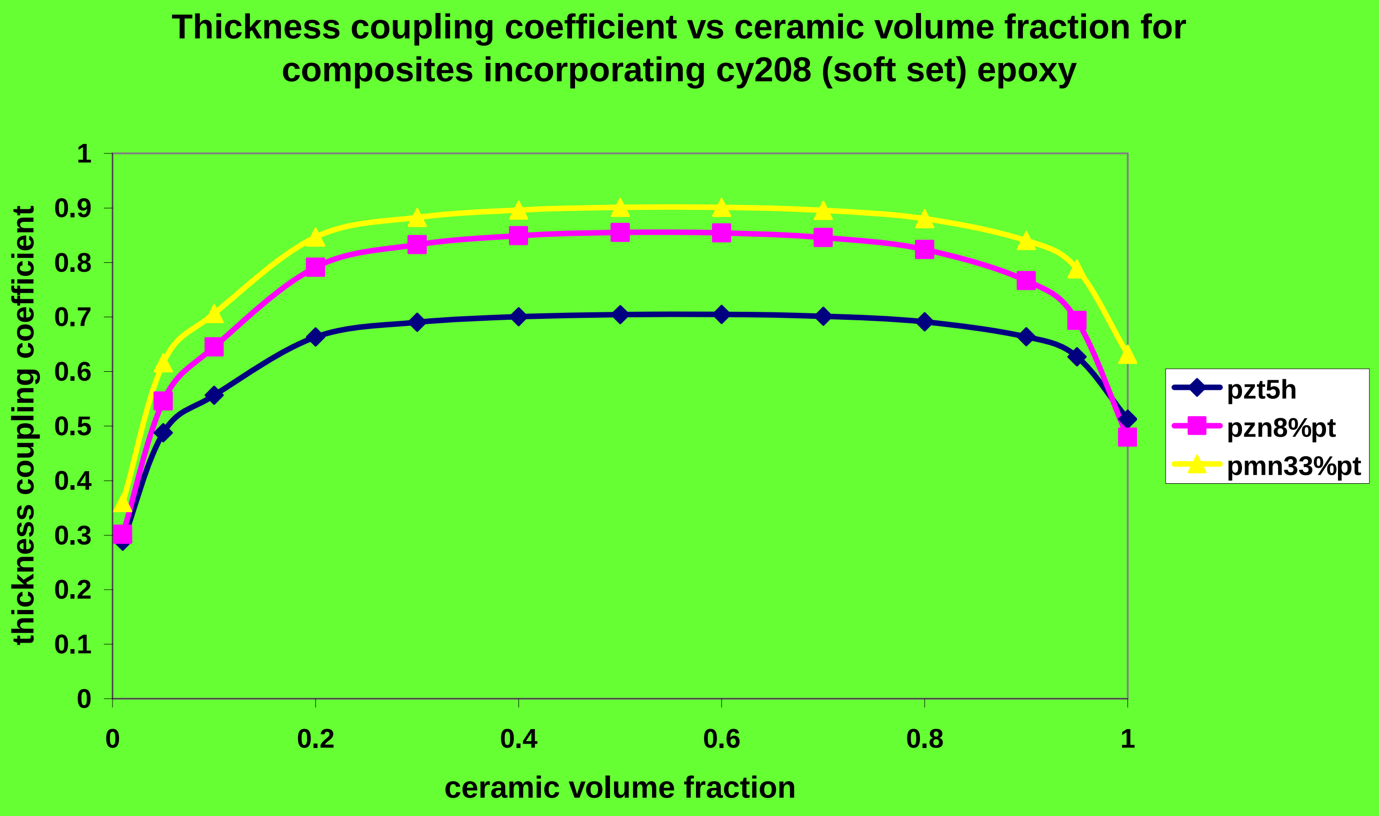
- Perovskite single crystals such as Pb($mg_{1/3}nb_{2/3}$)o $_3$ – pbtio$_3$ (PMN-PT) offer much improved piezoelectric properties compared with PZT ceramics. For example electromechanical coupling as high as 0.96 has been reported.
- Transducers made from single crystal material have vastly improved sensitivity and bandwidth because of the increased electromechanical coupling .
- Some issues with the technology:

1. It is currently difficult to grow large, high quality single crystals - therefore they are expensive.
2. The crystals can tend to chip and fracture during transducer manufacture unless the manufacturing process is modified.
3. The material properties are more sensitive to temperature.

Bandwidth Comparison
(LSM 1D Model - Impulse Excitation)

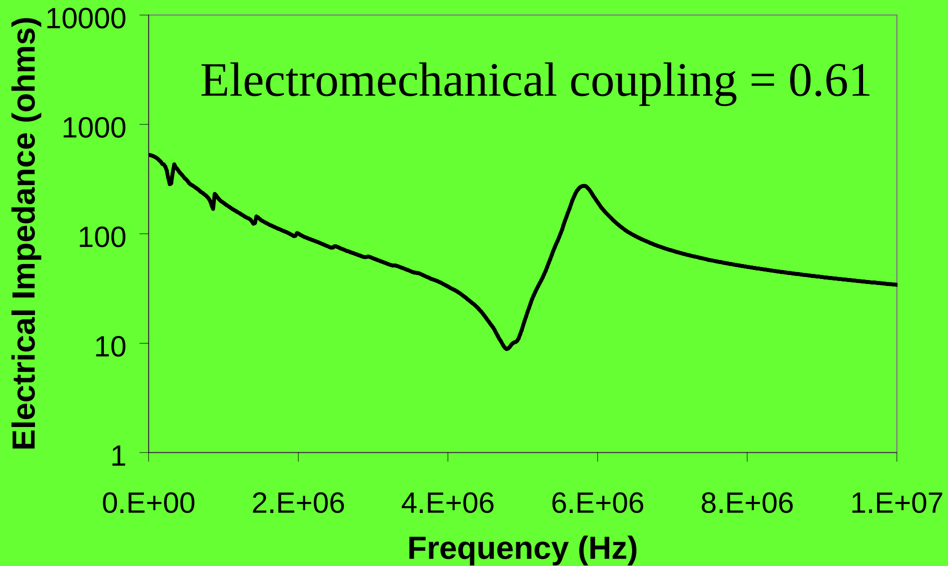


Electromechanical Coupling Coefficients

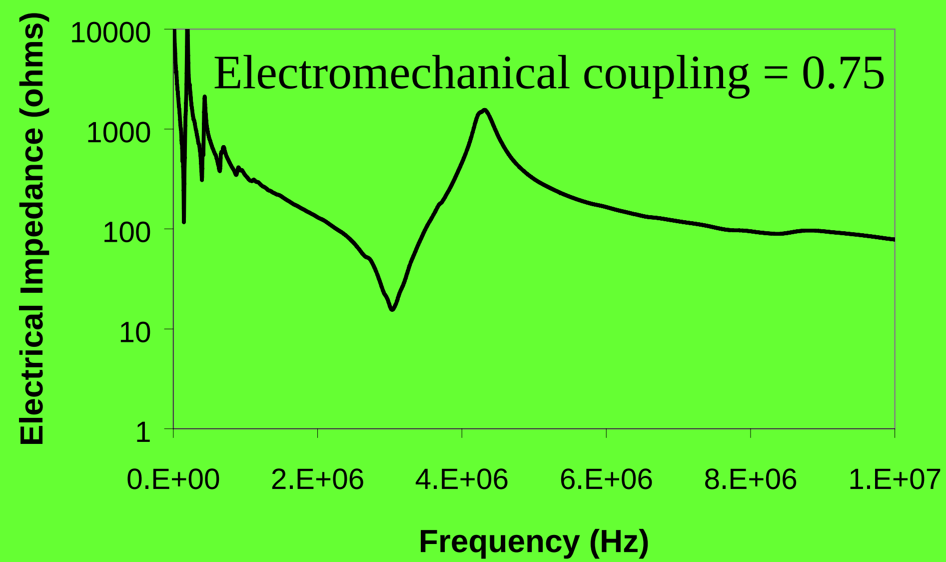


Experimental Results
(Transducers Have Dimensions 5mmx5mmx0.4mm)

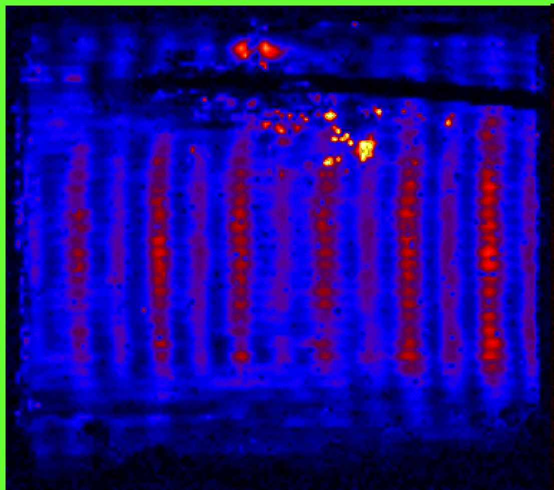
Pzt5h ceramic 2-2 composite

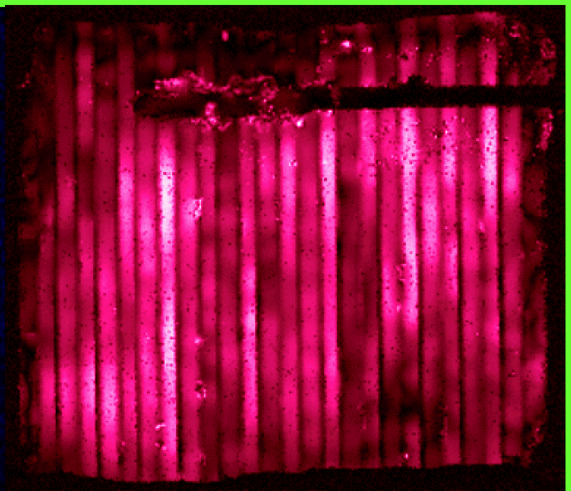


Pzn-8%pt single crystal 2-2 composite



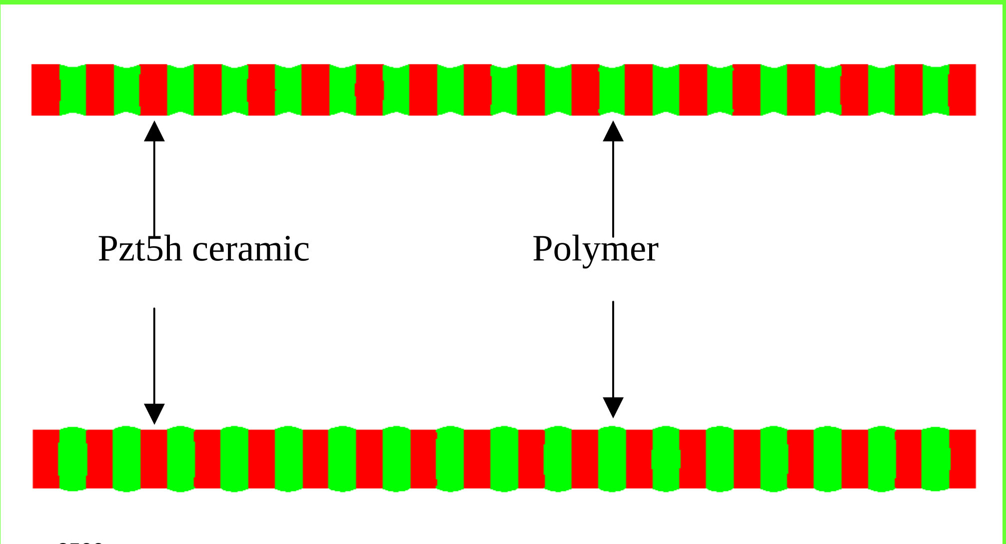
Laser scan of the surface displacement gives an average displacement of 4nm.

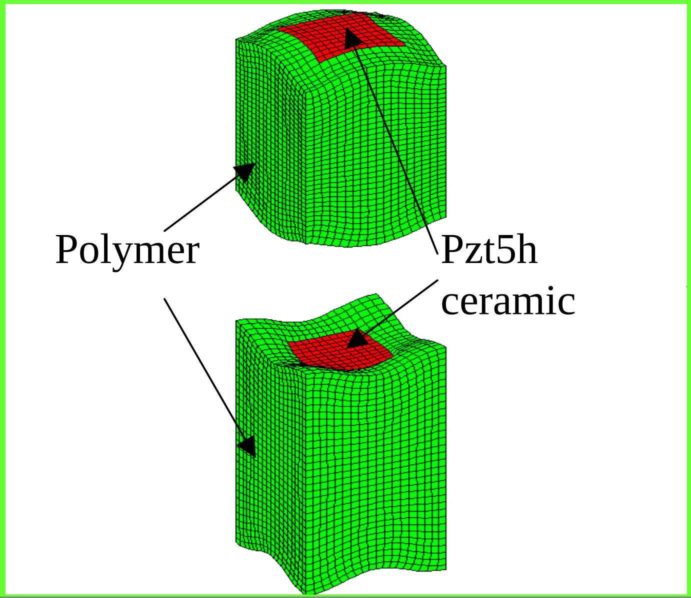


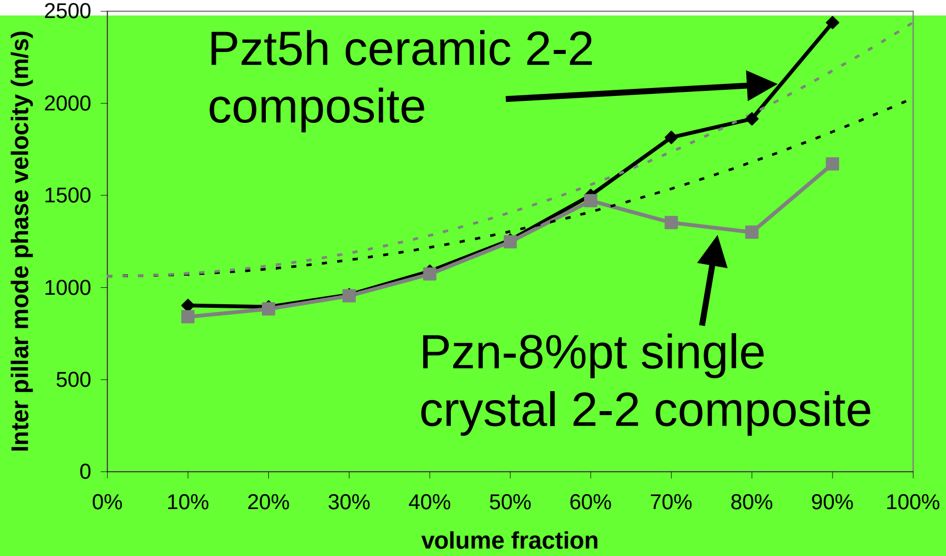


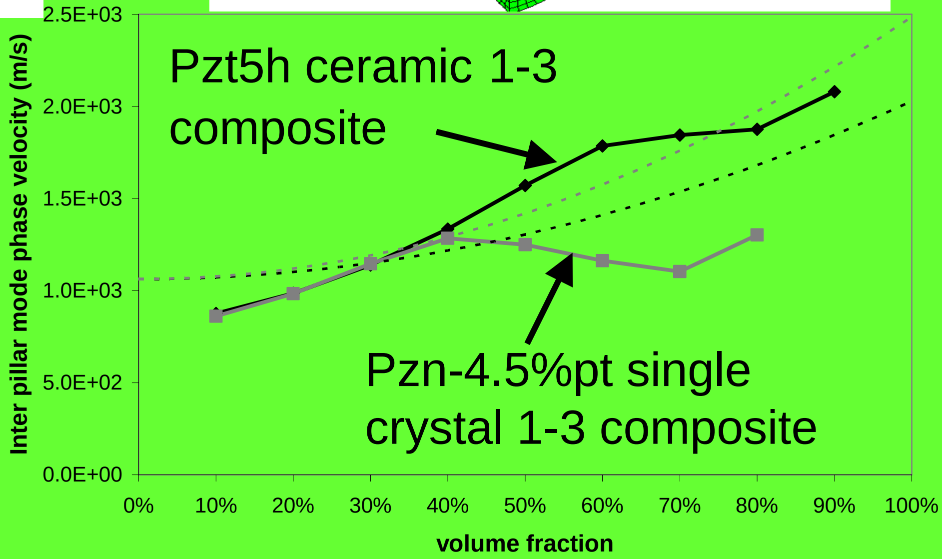
Laser scan of the surface displacement gives an average displacement of 9nm.

Inter Pillar Modes in Composites

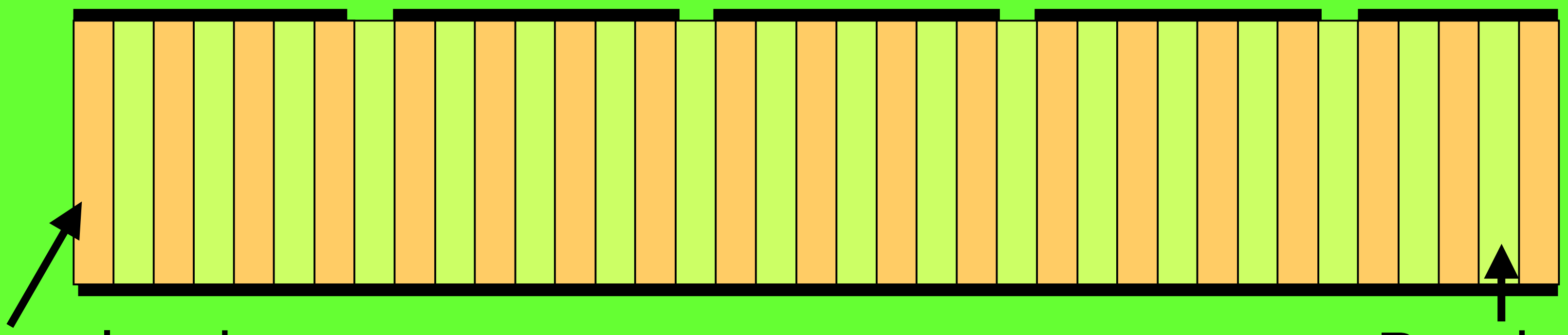






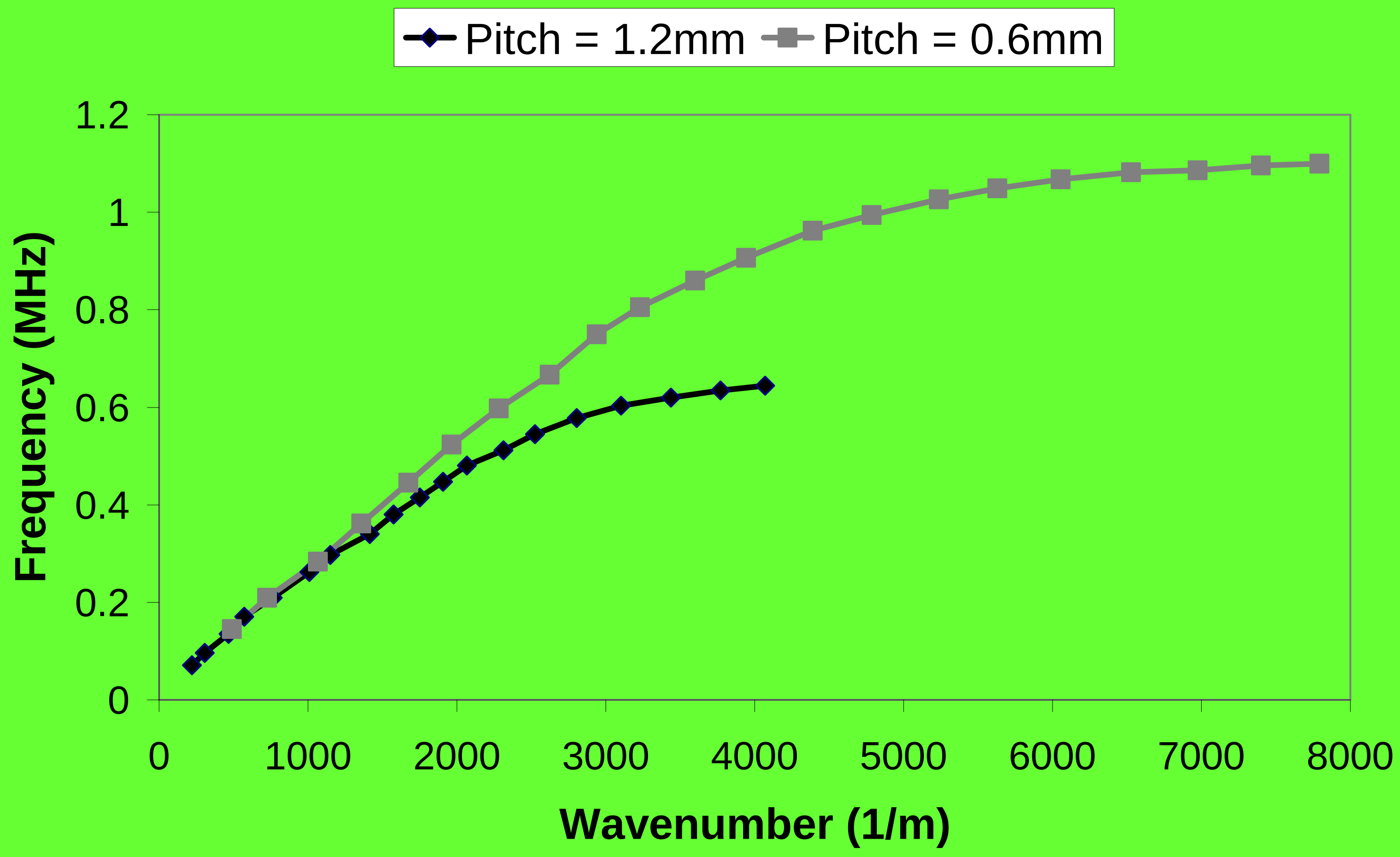


1D Arrays



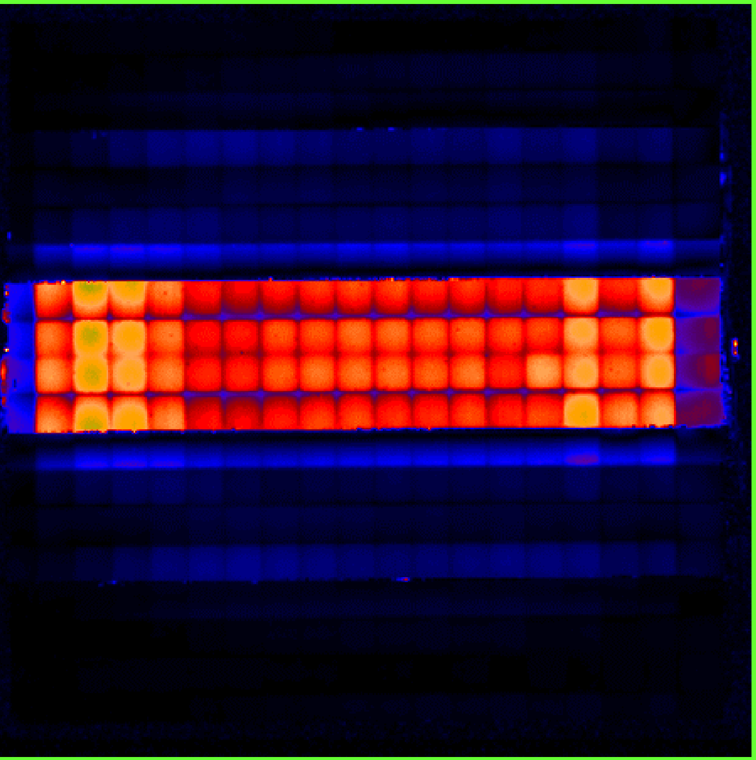
- Five array elements were patterned on to each composite substrate by scribing 4 cuts through the electrode in to the kerf of the composite.

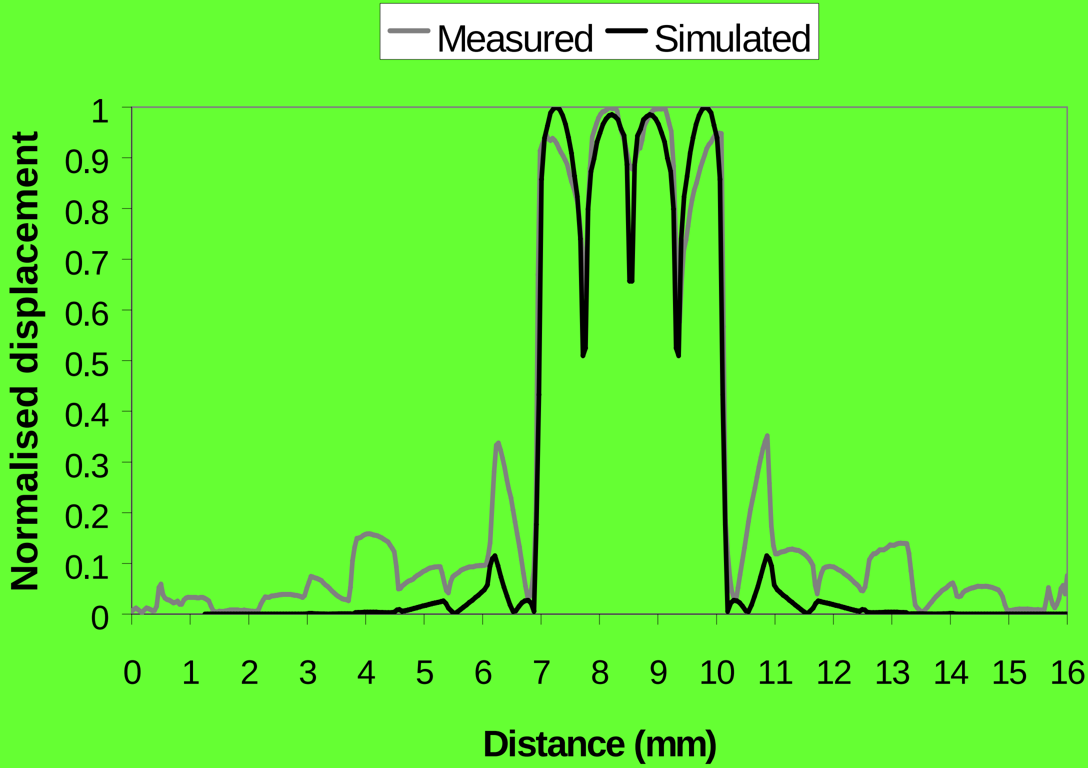
Composite Substrate S0
Lamb Wave Dispersion Curve



- The above graph is simulated data for the S0 lamb wave in a 50% volume fraction 2-2 pzt5h composite substrate. By doubling the pitch of the composite the S0 mode is “cut off” at a much lower frequency.

Pzt5h Array Cross Coupling

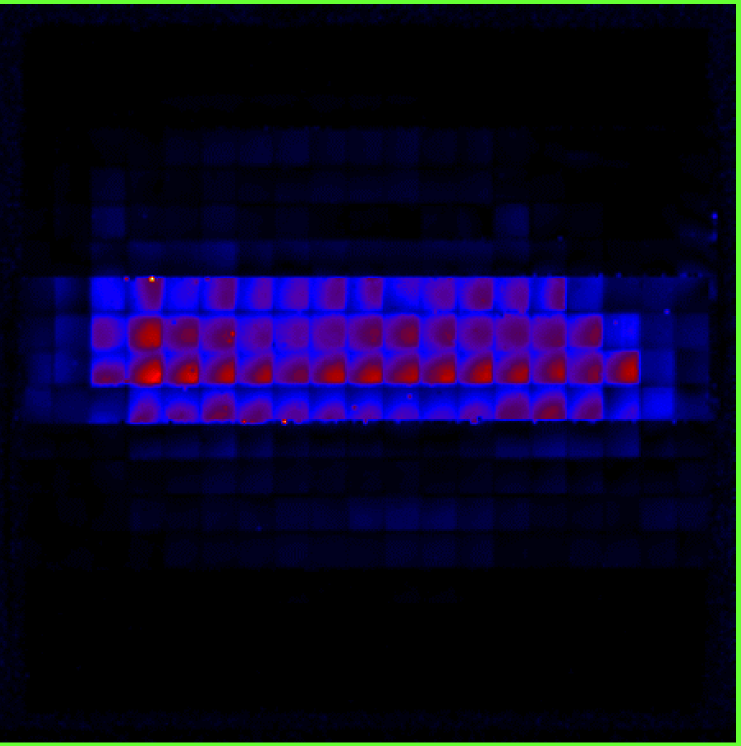


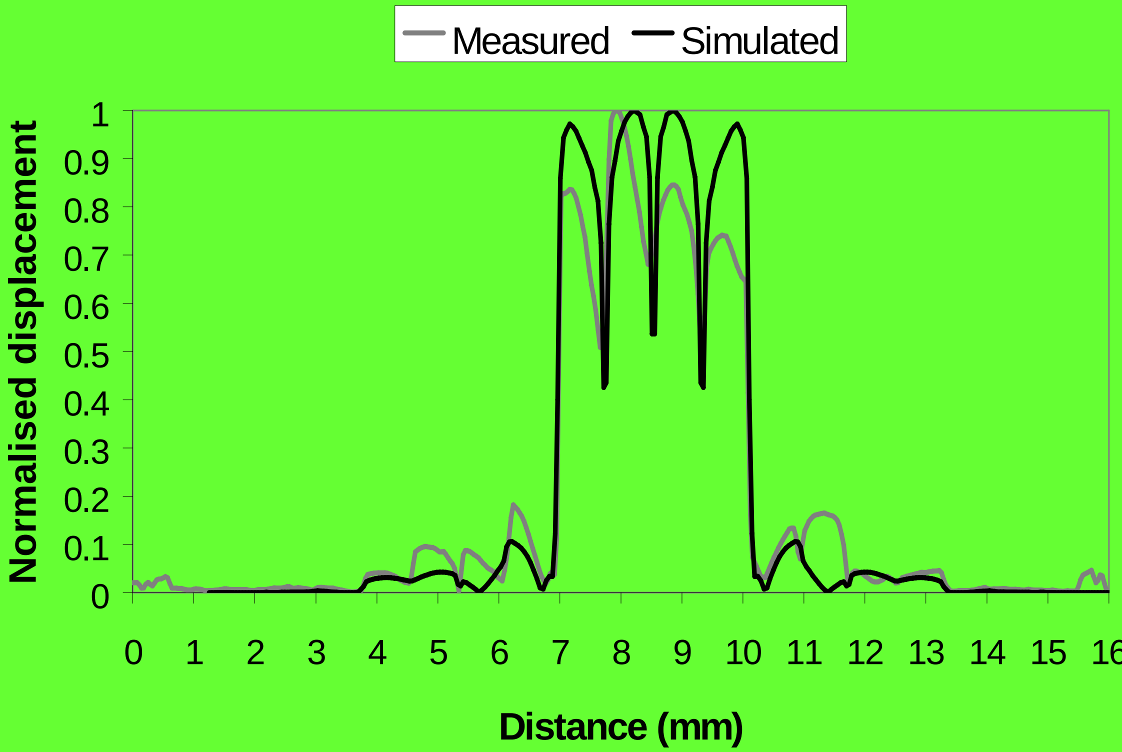


The above surface displacement image was taken while the array was operating at its resonance frequency of 1.01 MHz.

The maximum cross coupling into the adjacent elements is approximately –9 dB. While the maximum cross coupling into the outer elements is approximately –23 dB.

Pmn-pt Array Cross Coupling





The above surface displacement image was taken while the array was operating at its resonance frequency of 1.01 MHz.

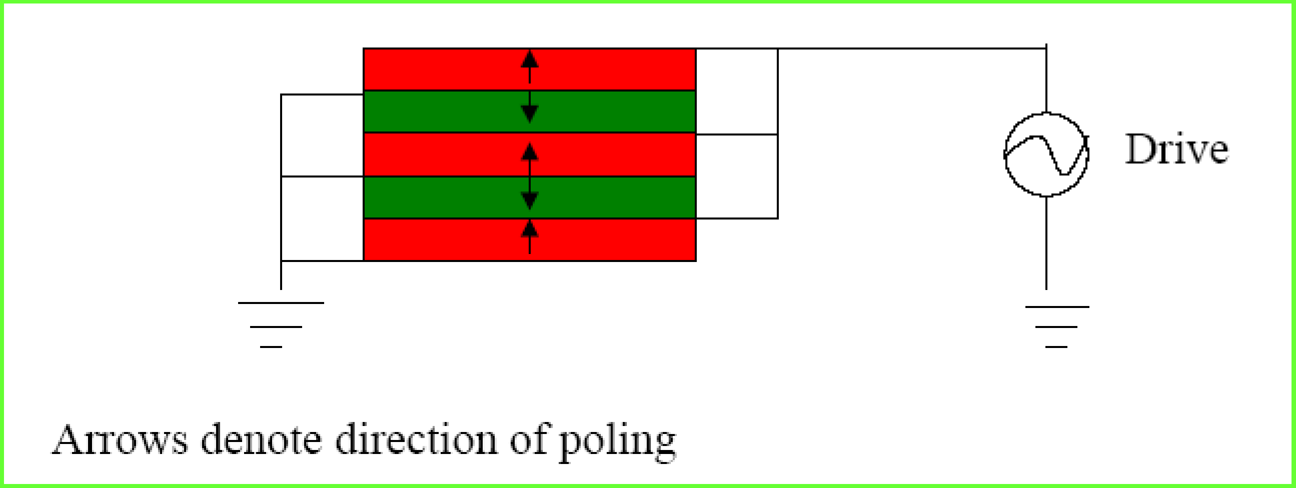
The maximum cross coupling into the adjacent elements is approximately –15 dB. While the maximum cross coupling into the outer elements is approximately –27 dB.

Conclusions

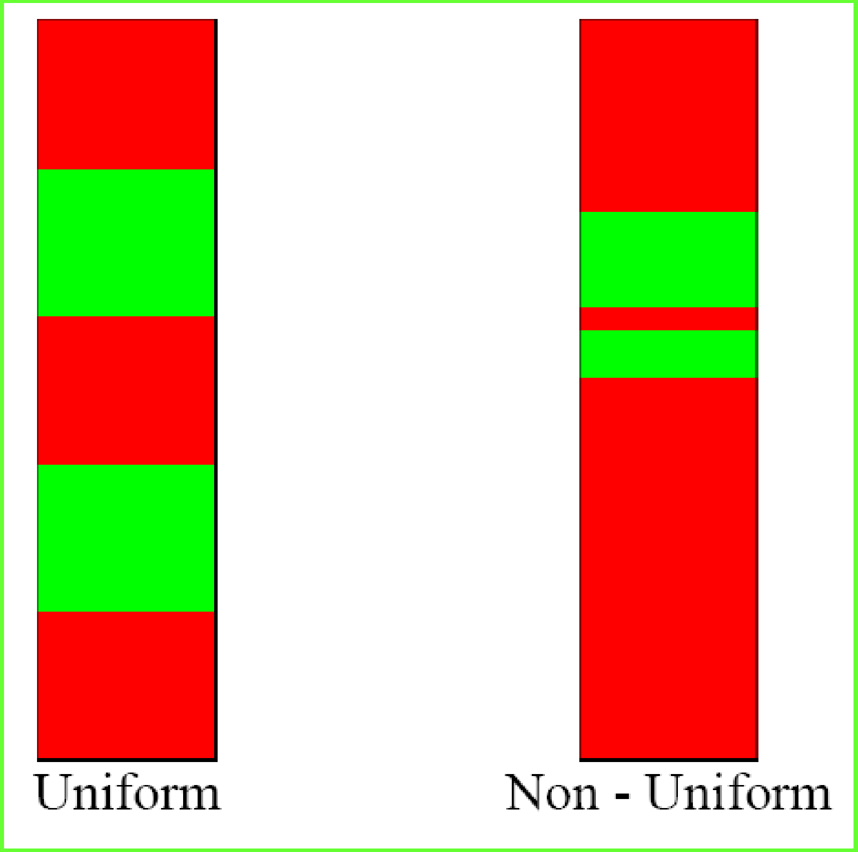
- Single crystal materials when configured as either a 2-2 or 1-3 composite offer greatly increased displacement and bandwidth compared with piezoelectric ceramics.
- The inter pillar mode behaviour of single crystal composites has been investigated and the frequency of inter pillar modes can be accurately predicted.
- The measured and simulated cross coupling in single crystal arrays is not significantly higher than for ceramic arrays.

Stacked Piezoelectric Composites

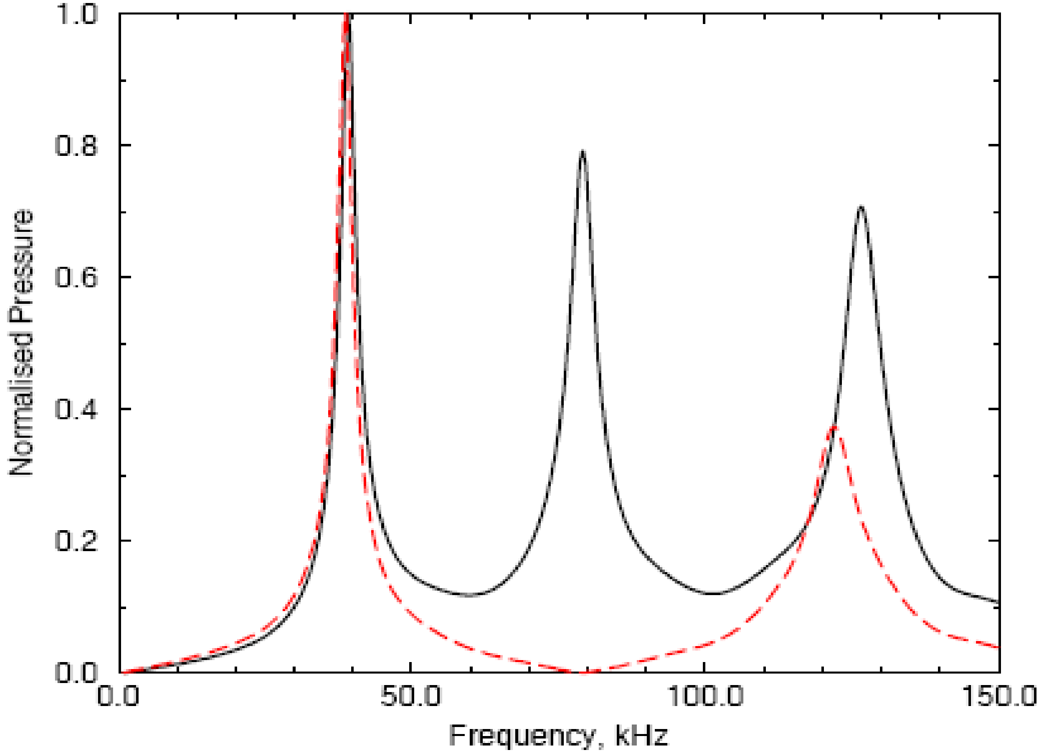
- Multilayer piezoelectric composites present a viable approach for the manufacture of low frequency sonar transducers
- Stacks are produced by bonding alternately poled piezoceramic mechanically in series and electrically in parallel



Non-uniform Layers

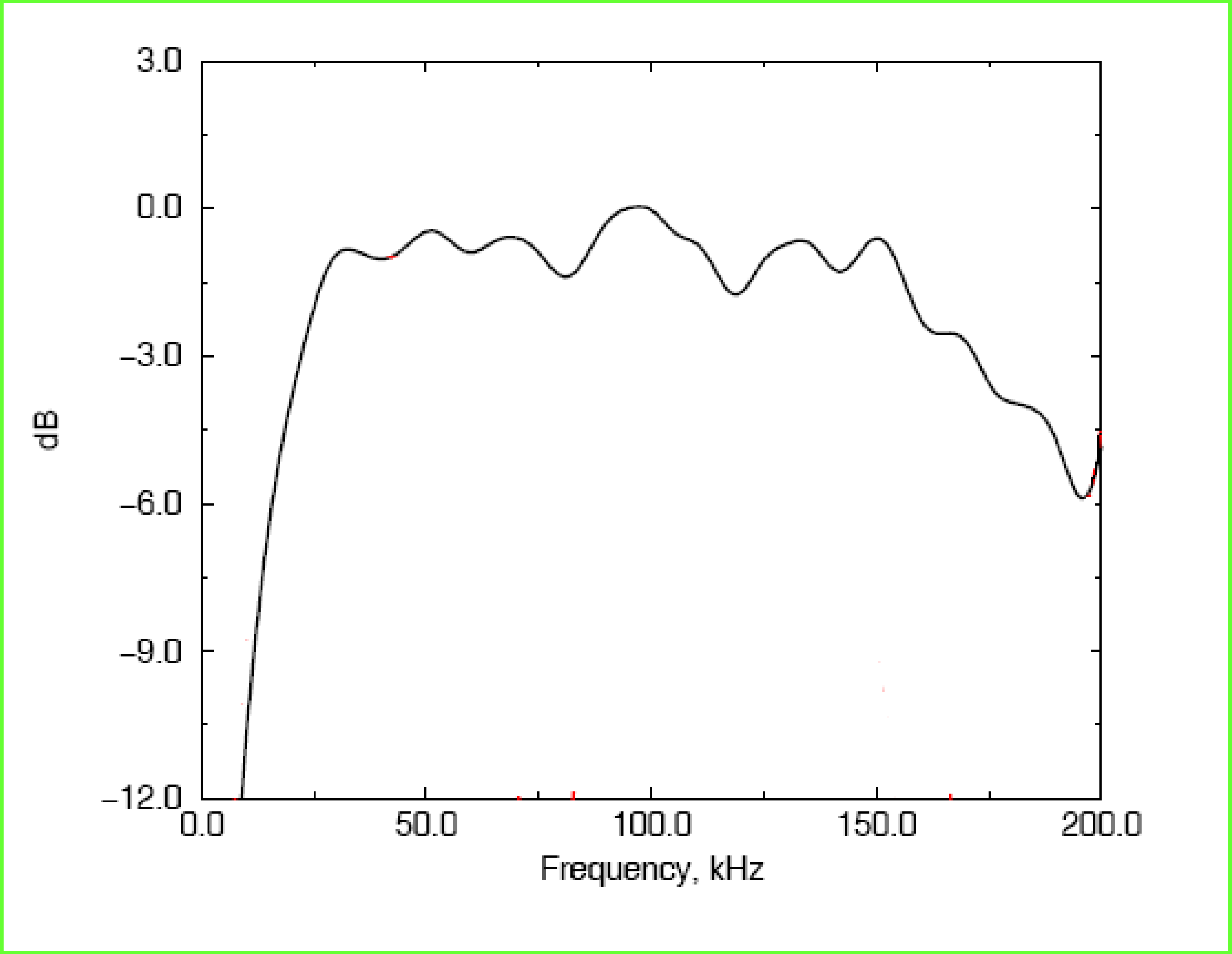


FEA Of Non-uniform Stack



4.77 – 2.39 – 4.77 – 9.55 – 19.10

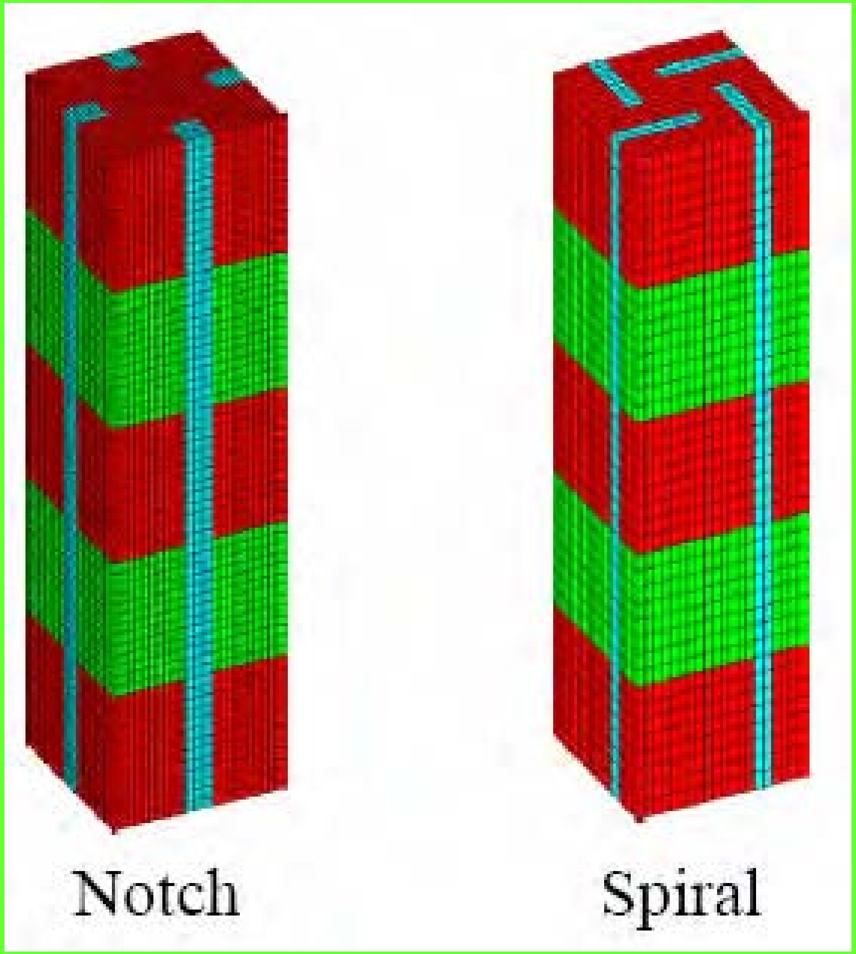
FEA of Non_uniform Super 1-3



3-1 Connectivity Stacks

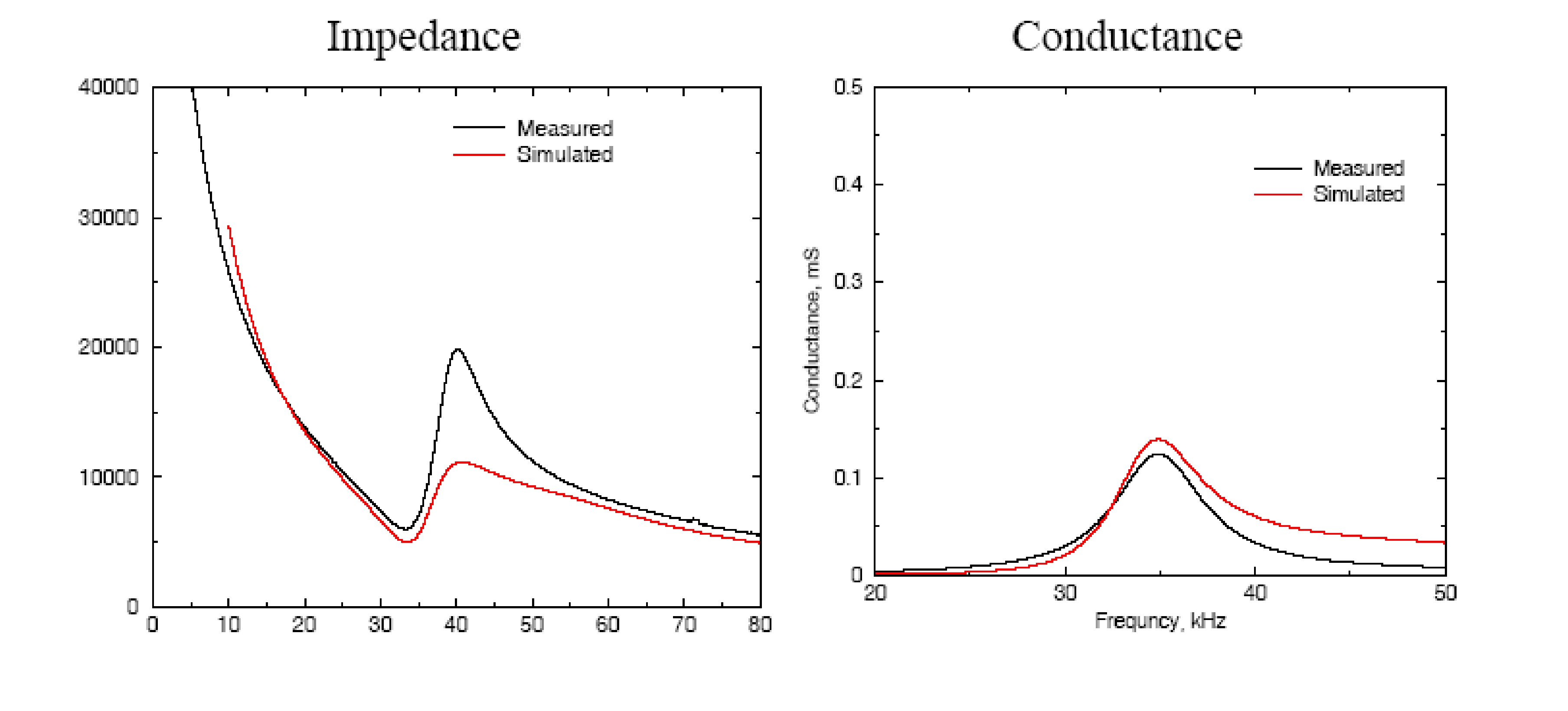
Examples of 3-1 connectivity

- Piezoceramic blocks are bonded together prior to dicing
- The stacks are then diced to retain the connectivity of the surface electrodes
- Gives perfect registration of the microstructure in the thickness dimension – improved structural integrity

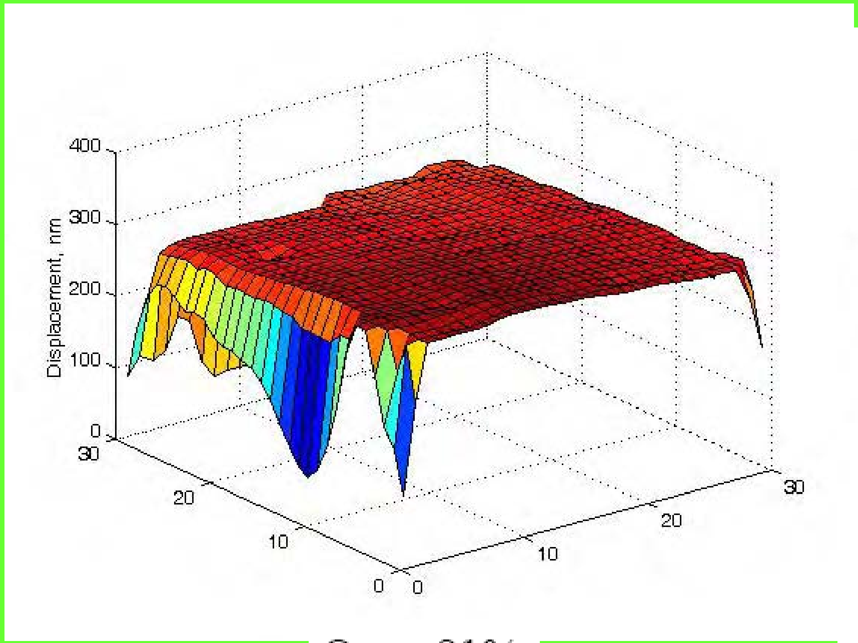


3-1 Connectivity Stacks

- Soft set encapsulated stack

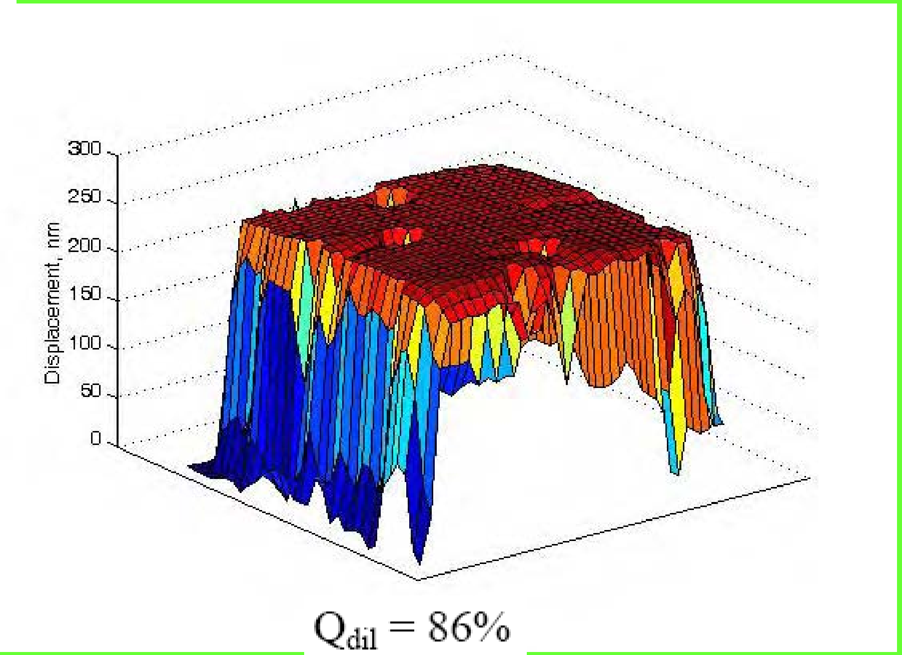


3-1 Connectivity Stacks



$Q_{dil} = 81\%$

$Q_m = 168$

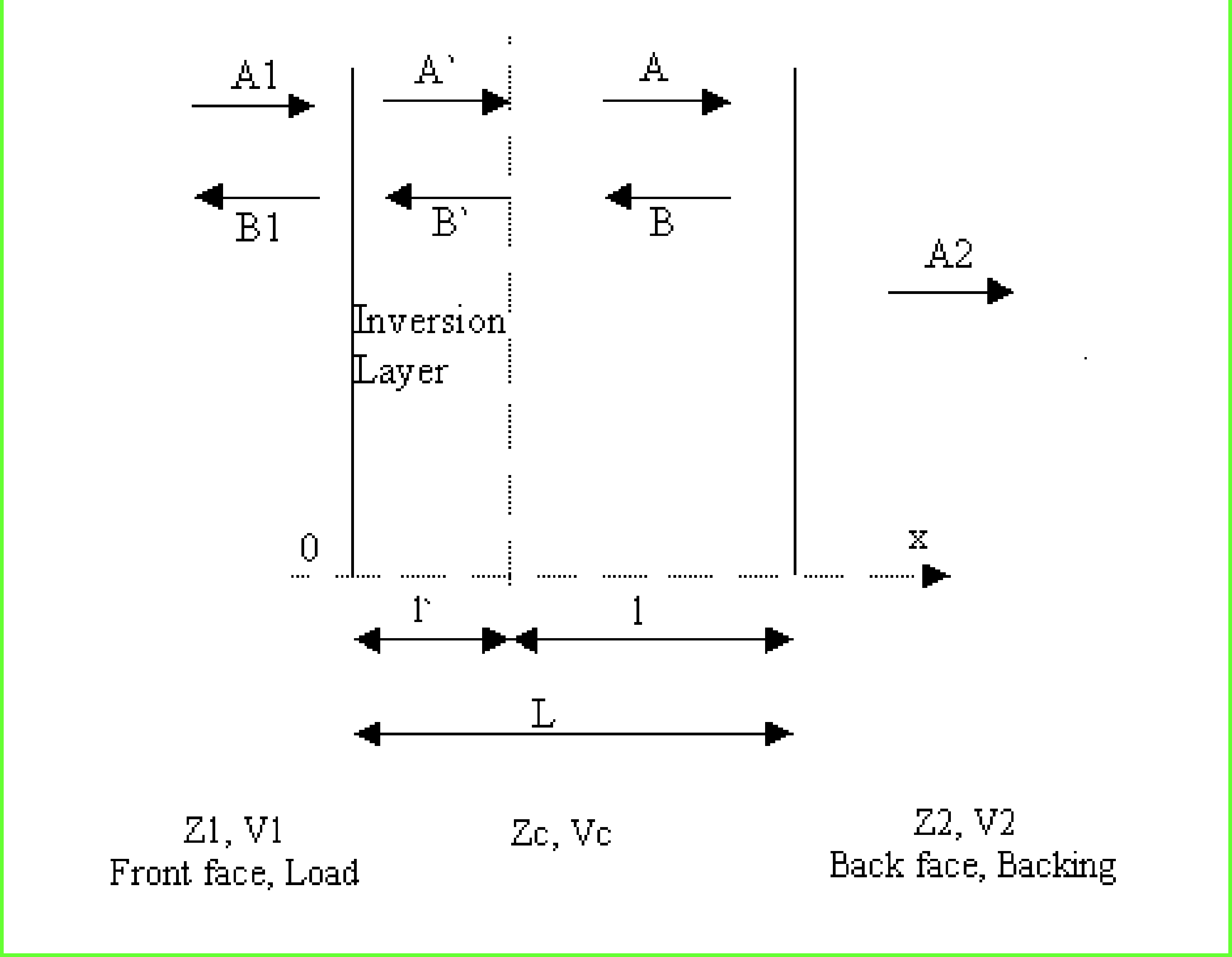


$Q_{dil} = 86\%$

$Q_m = 164$

- Experimental results for the two 3-1 connectivity designs 75% ceramic volume fraction – hard set polymer
- Both designs satisfy the requirements of uniform surface displacement

Inversion Layer Device



Inversion Layer Receiver

- Receive Transfer Function

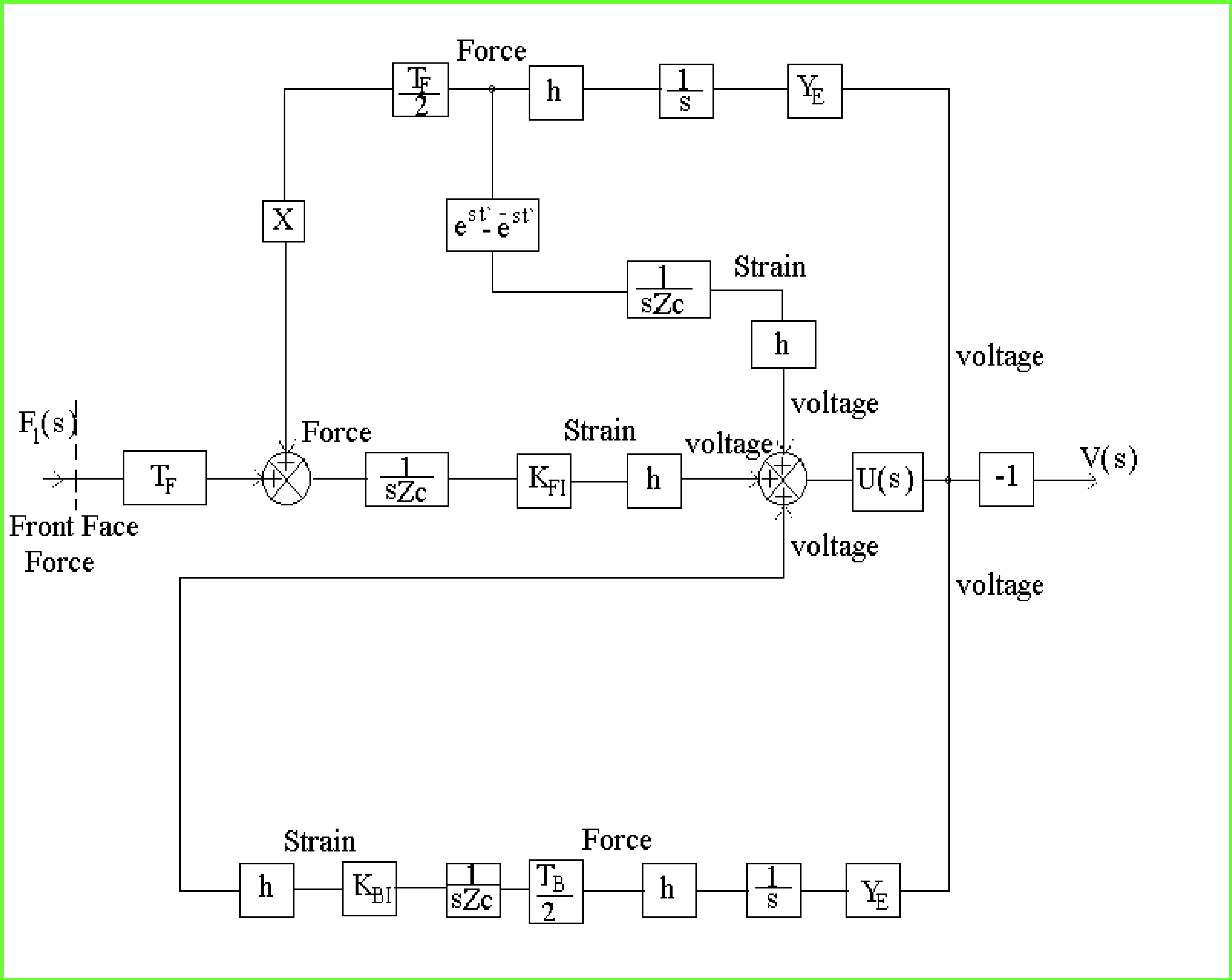
$$\frac{V(s)}{F1(s)} = \frac{\dfrac{-hU(s)T_F K_{FI}(s)}{sZc}}{1 - \dfrac{h^2 U(s)}{s^2 Zc Z_E(s)}\left[X K_{FI}(s)\dfrac{T_F}{2} + K_{BI}(s)\dfrac{T_B}{2} + e^{st} - e^{-st} \right]}$$

$$K_{FI}(s) = \frac{-e^{-sT} + 2e^{-st} - 1 - R_B e^{-sT} + 2R_B e^{-2sT} e^{st} - R_B e^{-2sT}}{\Delta}$$

$$K_{BI}(s) = \frac{e^{-sT} - 2e^{-sT} e^{st} + 1 + R_F e^{-sT} - 2R_F e^{-sT} e^{-st} + R_F e^{-2sT}}{\Delta}$$

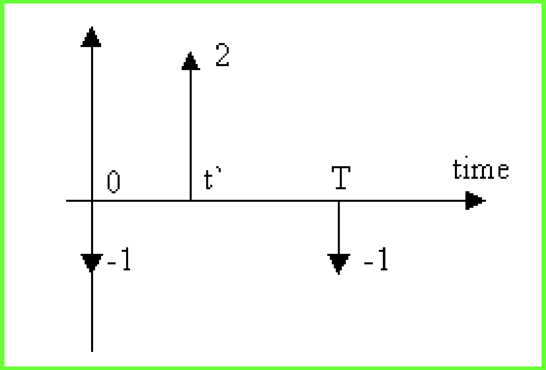
$$X = \left[\frac{Z1}{Zc} e^{s(l'/vc)} - \frac{Z1}{Zc} e^{-s(l/vc)} - 1 + e^{s(l/vc)} + e^{-s(l'/vc)} \right]$$

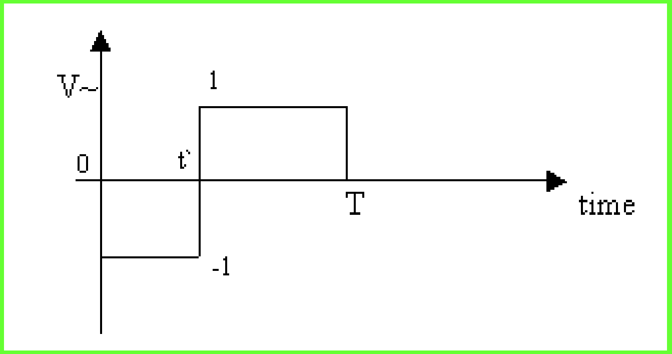
Receive Feedback Model



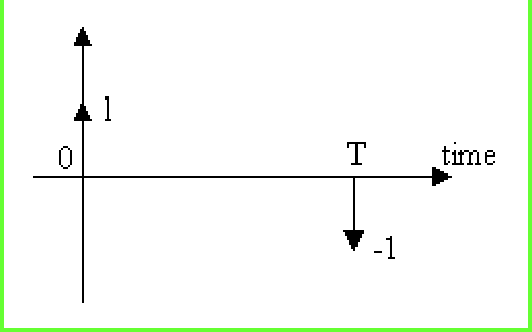
Receiver Impulse Response

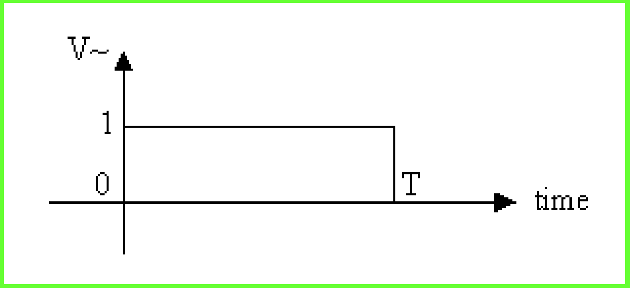
- Inversion Layer Receiver





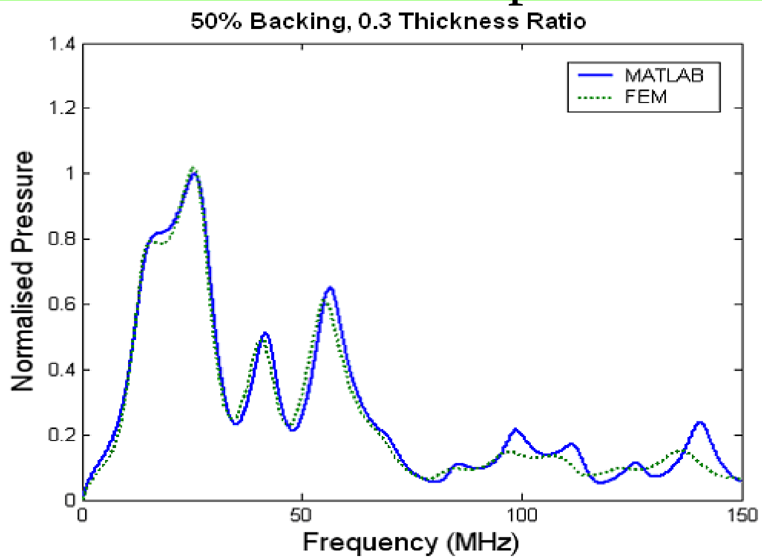
- Normal Receiver

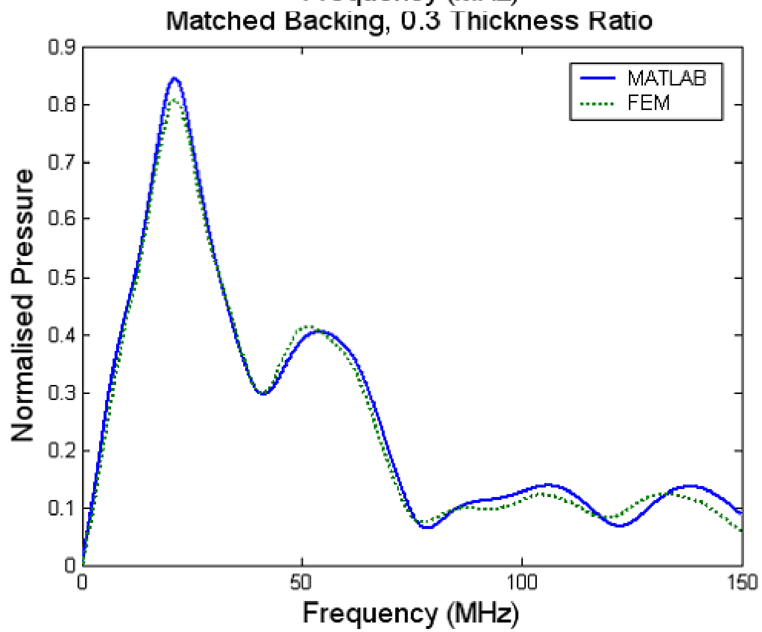




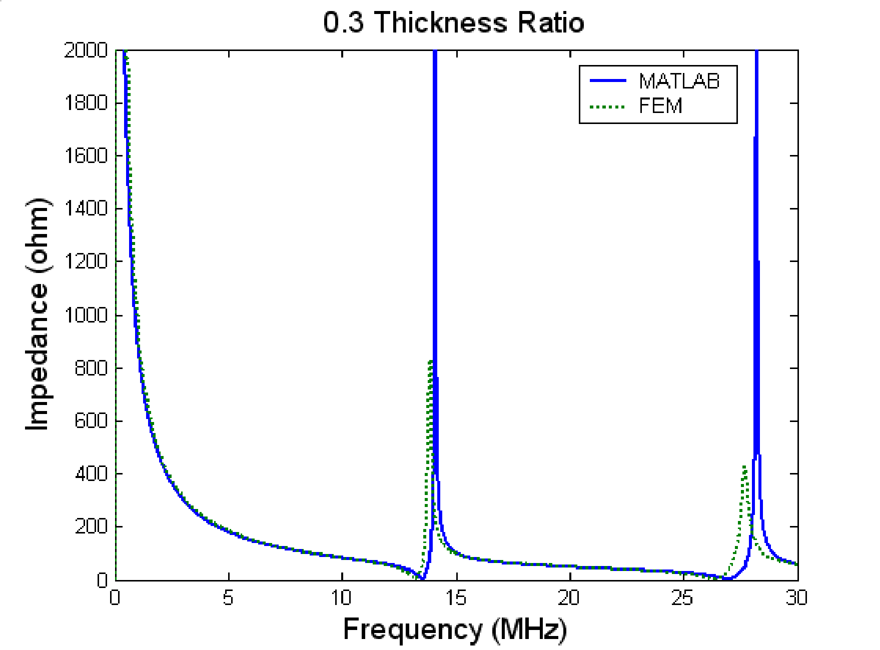
Simulation

- Transmit Response

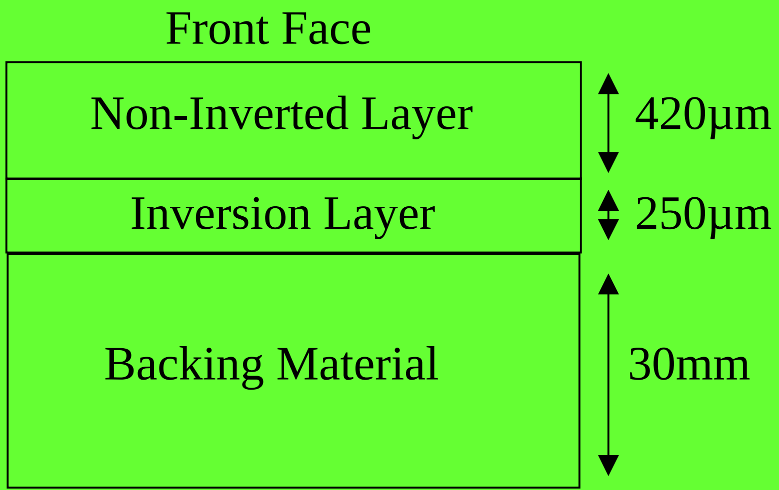




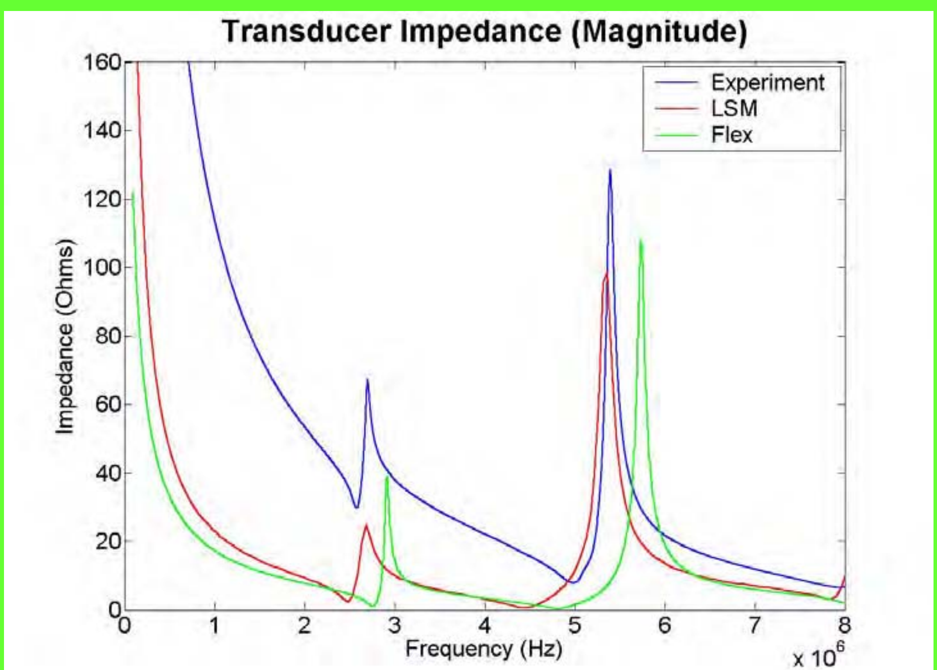
- Transducer Impedance Plot

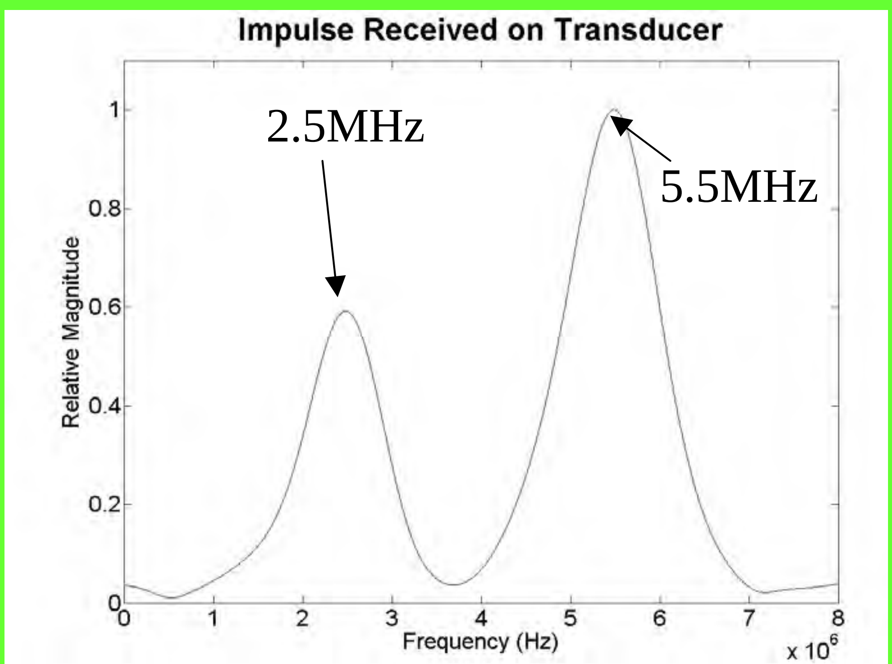


Back Face Inversion Layer Device



- •1-3 composite, PZT5H / Hardset, 50%VF
- •Lateral dimensions 20x20mm
- •Experimental results correlate well with simulation
- •Impulse response shows good harmonic separation





Appendix 3g

Frederic DeVaud

Evaluation of a “Bat Inspired” Ultrasonic Imaging System

F. Devaud
PhD Student
Centre for Ultrasonic Engineering
Institute for Communications and Signal Processing
University of Strathclyde

Overview

- Aims:
  - Study the bat's auditory system and processing techniques
  - Apply innovative imaging process to the Ultrasonic domain
- Presentation Summary:
  - Facts on bats
  - Signal processing technique
  - Simulation
  - Conclusion

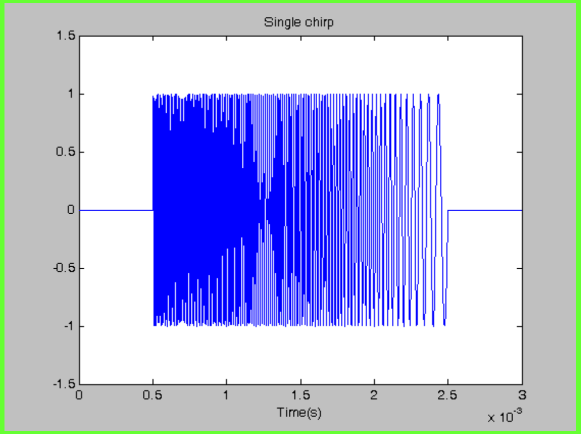
Some facts on bats

- Experiments have shown that bats possess a sub-millimetre resolution
- Very impressive resolution given the emission wavelength (~3.4mm for 100kHz)

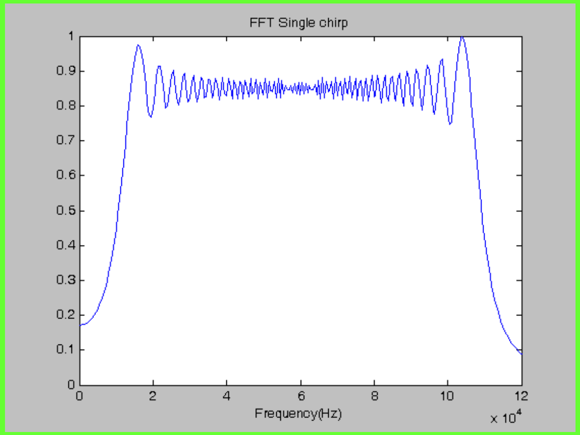
Bat's echolocation process

- How do bats recognise their target ?
  - Use of chirp signals to analyse their surroundings
  - Identification of acoustic signature
  - Determination of reflective points along the range-axis

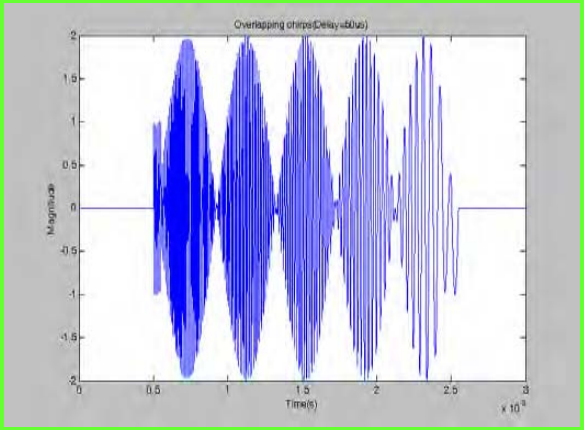
Property related to overlapping chirps



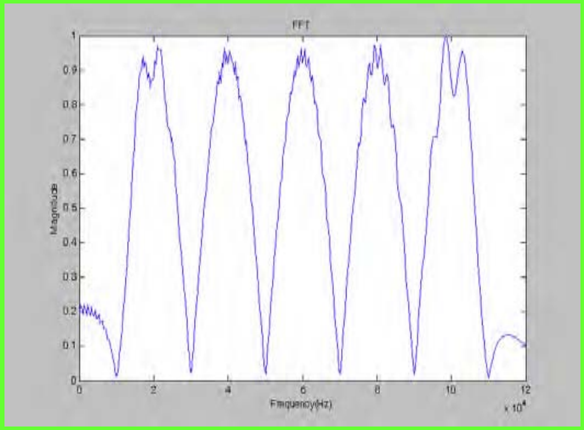
Single Chirp



Frequency Spectrum



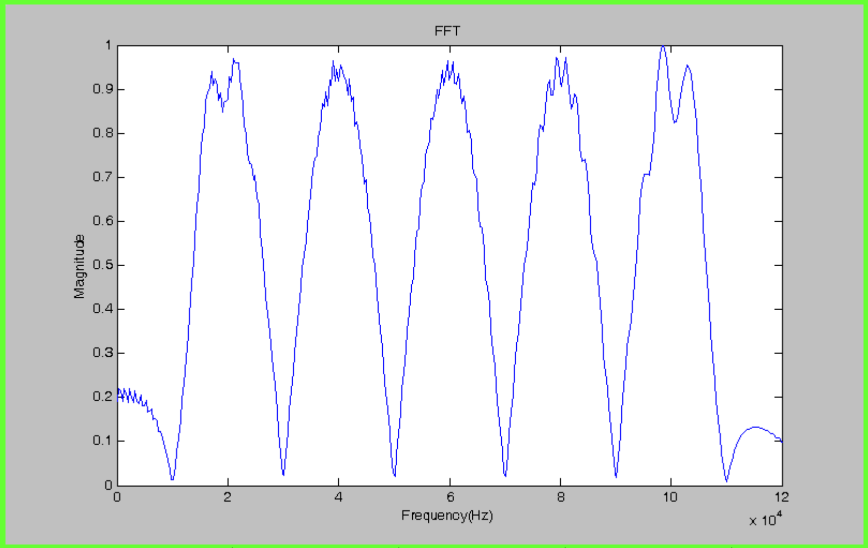
Two overlapping chirps(50 µs)

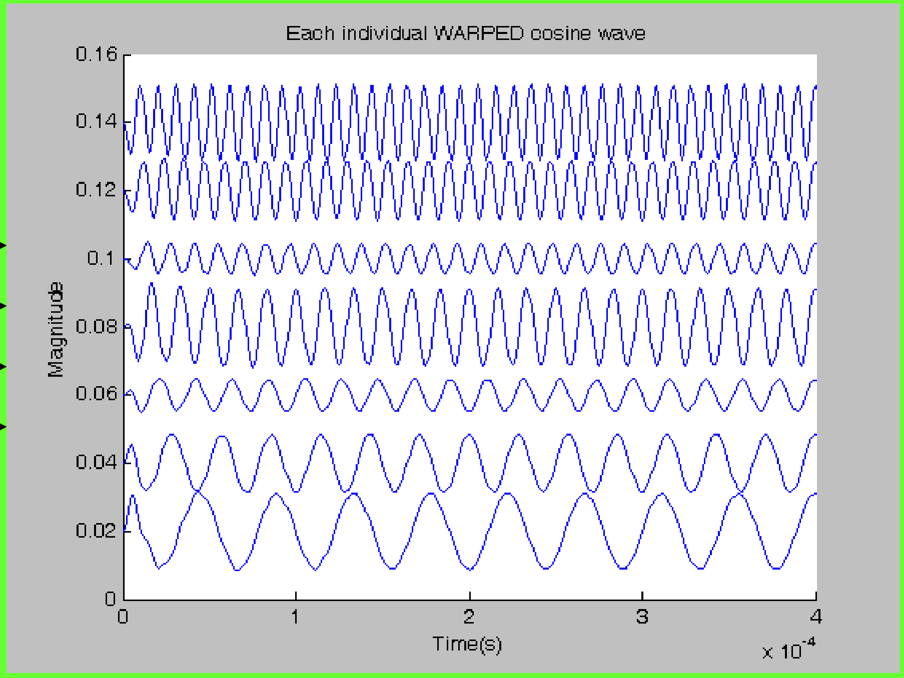


Frequency Spectrum

Frequency to time transform

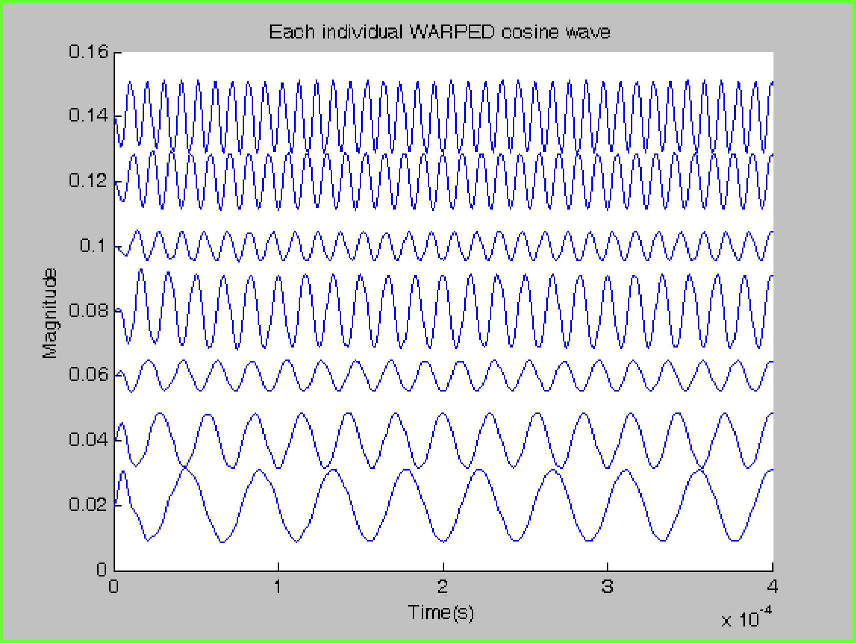
- Decomposition of the spectrum in subbands



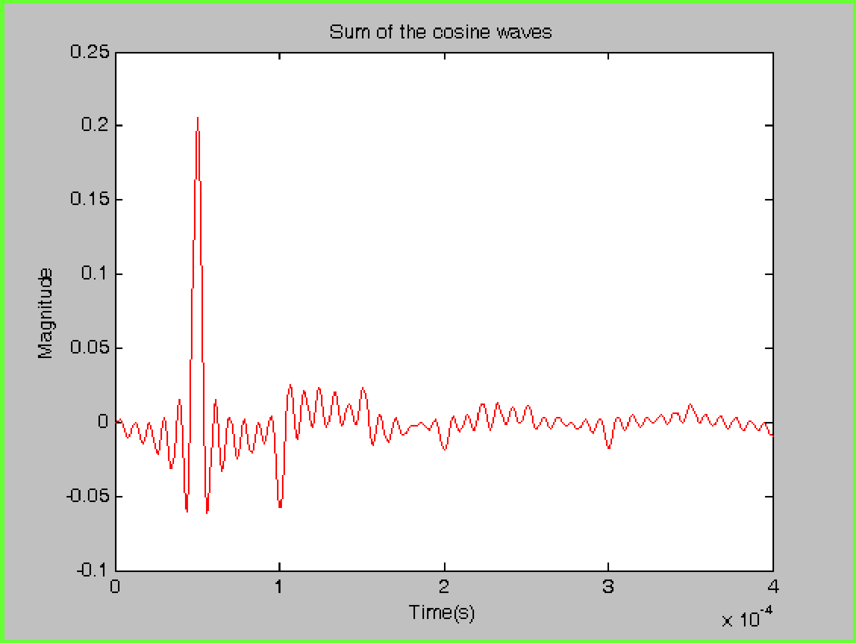


81 subbands

Transform the spectrum to a time signal



Sum

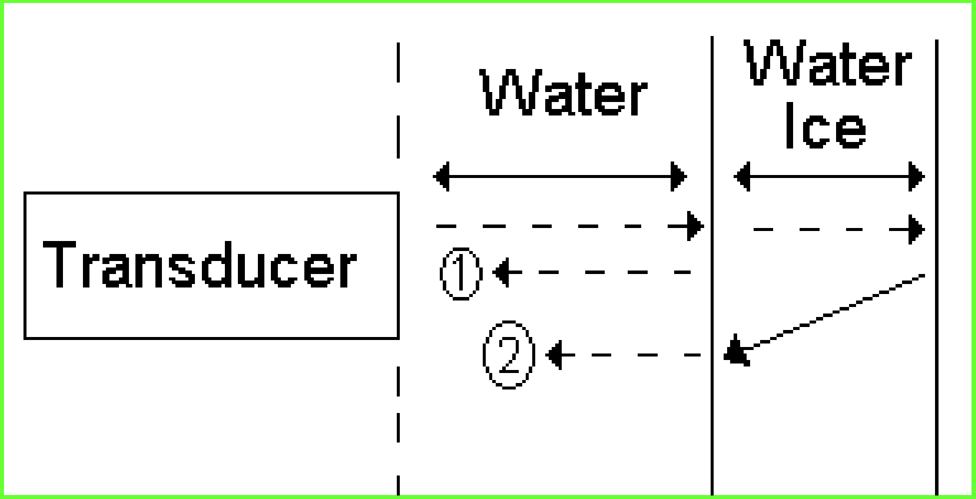


Cosine waves individually

Sum of the cosine waves

Simulation

- Simulation of a 1-D Ultrasonic system: Measure of the resolution achievable



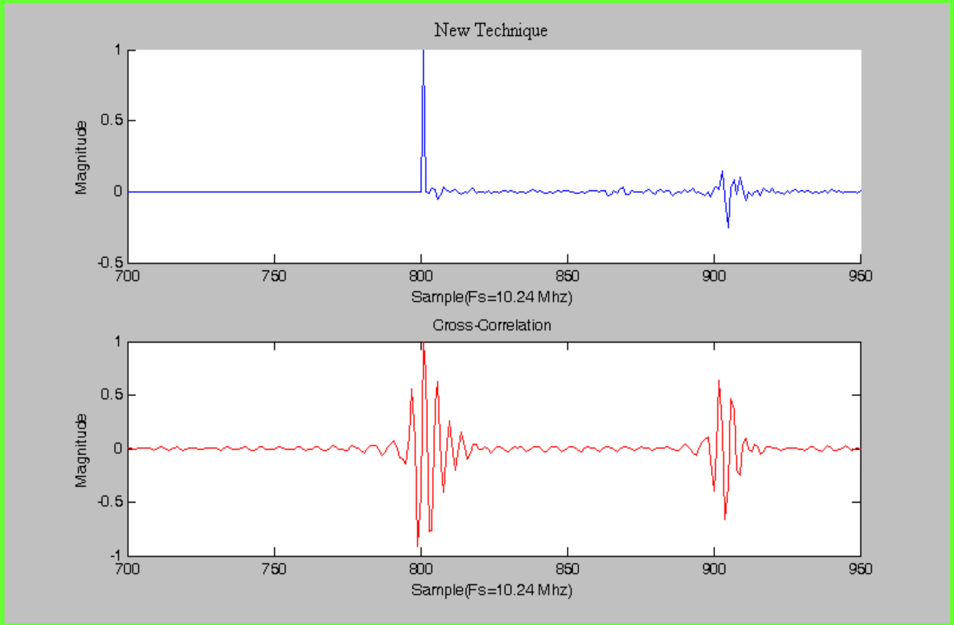
- λ_{water}= 592 µm
- $\lambda_{water\ ice}$= 1.59 mm

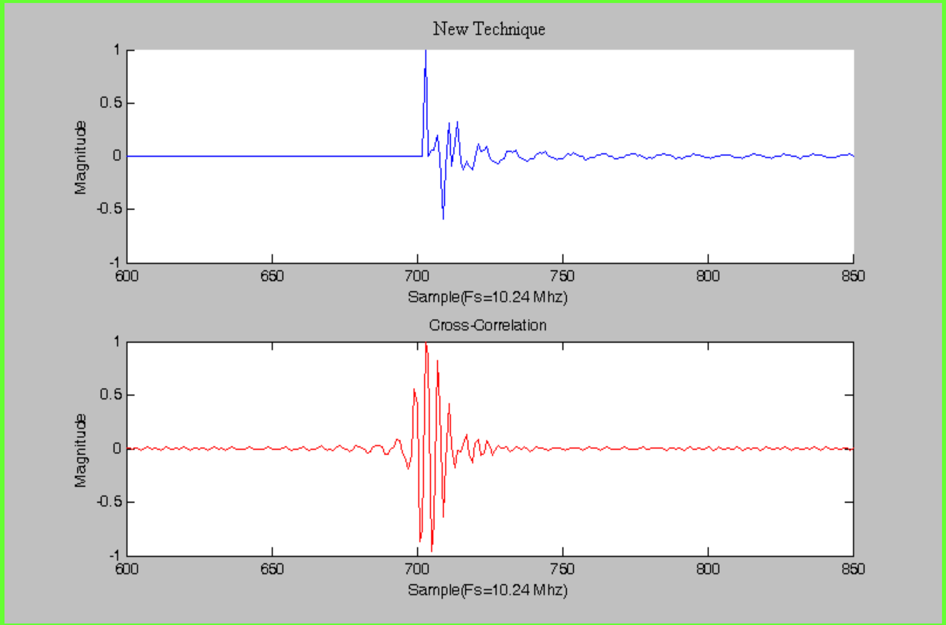
Results

- Thickness = 20 mm
- Thickness = 1 mm

New Technique

New Technique





Cross-Correlation

Cross-Correlation

Results

Thickness (mm)	Theory (μs)	Cross-Correlation (μs)	New Technique (μs)
20	10	10	10
5	2.5	3	3
4	2	2	2
3	1.5	No result	1
2	1	No result	1
1	0.5	No result	1

Conclusion & Further work

- Feasibility of a bat's inspired model
- Study the possibility to extend the technique to multiple echoes

Evaluation of a “Bat Inspired” Ultrasonic Imaging System

F. Devaud
PhD Student
Centre for Ultrasonic Engineering
Institute for Communications and Signal Processing
University of Strathclyde

Appendix 3h

Andrea Trucco

Exploiting very short arrays

Andrea Trucco, Stefania Repetto
Dept. of Biophysical and Electronic Engineering (DIBE)
University of Genova, Italy

May 2004

Introduction (1)

Is it possible to achieve a good spatial directivity by using a receiving aperture that is shorter than the wavelength?

- Often, natural bioacoustics systems show excellent and complex performances in spatial filtering:
  - the human hearing apparatus
  - the echolocation system in dolphins

Introduction (2)

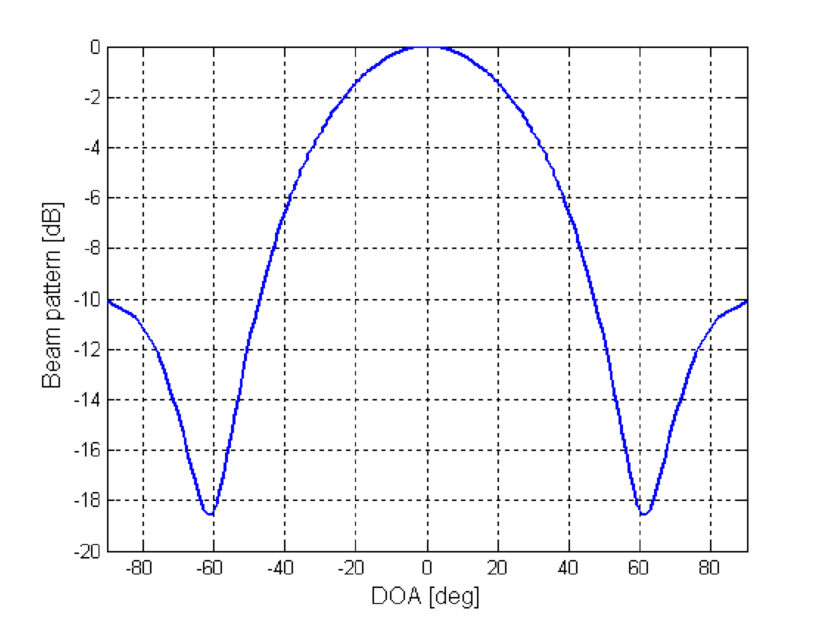
- Typical bioacoustics signals are **wide-band**:
  - the wavelengths related to the highest spectrum portion are shorter than the receiving aperture
  - the wavelengths related to the lowest spectrum portion are longer than the receiving aperture
- In this study, we do not try to reproduce the performances of a bioacoustics system

Introduction (3)

- We simply try to design a good **spatial filter**:
  - using a short receiving aperture of omni-directional sensors
  - obtaining performances that are stable over a wide-band spectrum
  - without any knowledge on the statistics of the received signals
- If we succeed on this task, we can exploit the designed system like a building block in emulating bioacoustics systems

Engineering approach (1)

- The engineering approach to achieve a spatial filter relies on **array signal processing**
- **Directivity** = (SNR)***array*** / (SNR)***omni-directional sensor***
- The directivity is strictly related to the **beam pattern** of the receiving array
- A normalized beam pattern shows the attenuation of signals coming from directions different from the steering one



Engineering approach (2)

Is it possible to achieve the same beam pattern for all the frequencies of a wide-band spectrum by using a given (short) receiving aperture?

- If yes, a typical application related to bioacoustics systems, is to design hearing aids of new generation

The hearing aid problem

- **Aim**: to improve the speech intelligibility by a spatial filter that increases the SNR **(abating sounds coming from directions different from that of the desired speech)**
- Available aperture: about 12 cm
- Frequencies to be processed: from 450 Hz to 3600 Hz, i.e., 3 octaves
- Wavelength interval: from 10 cm to 85 cm
- **The aperture is 0.14λ to 1.2λ**
- Possible array location: necklace or **glasses**

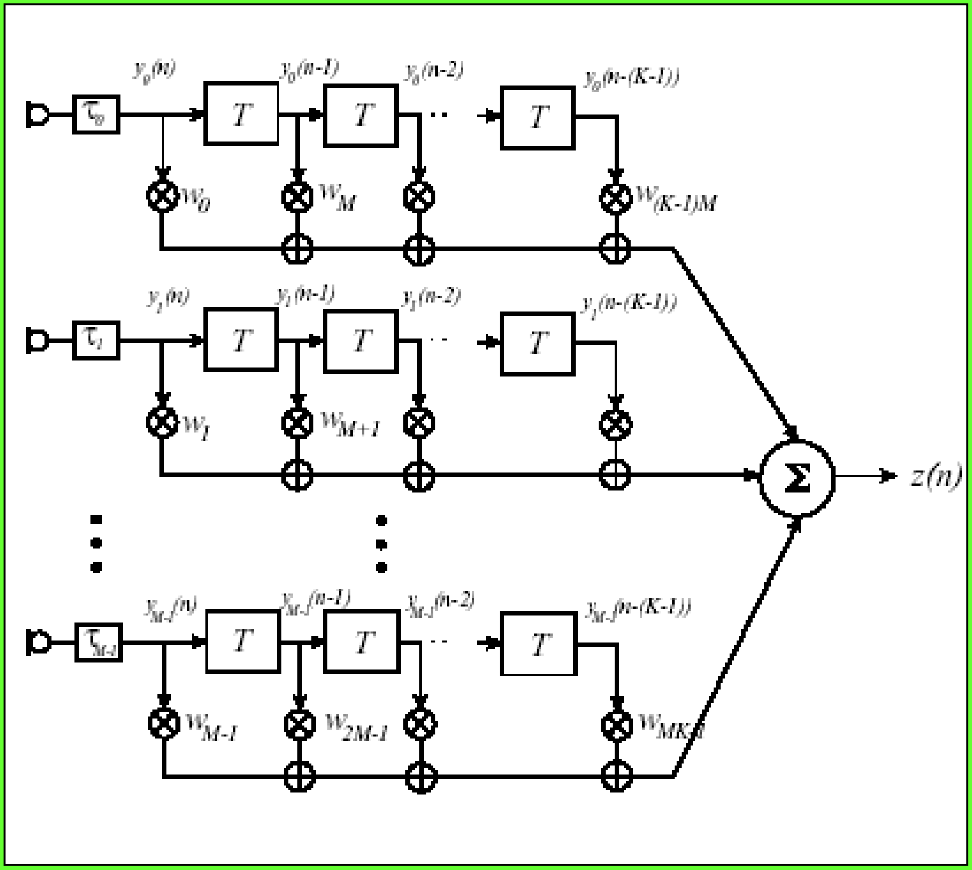
Hearing aid set-up

Hypothesized solution:

- array of 8 microphones, equally spaced over an aperture of 12 cm
- fixed steering in the broadside direction
- wide-band, data-independent beamforming
- quasi-constant beam pattern from 450 Hz to 3600 Hz, i.e., frequency-invariant beamforming

Wide-band beamforming (1)

- In traditional **narrow-band beamforming**, signals collected by the sensors are scaled by weight coefficients, delayed and summed
- The vector of the weight coefficients is called weighting window
- **Wide-band beamforming** uses **a FIR filter for each sensor** instead of a simple weight coefficient
- The frequency response of a filter represents the weight coefficient over frequency



Wide-band beamforming (2)

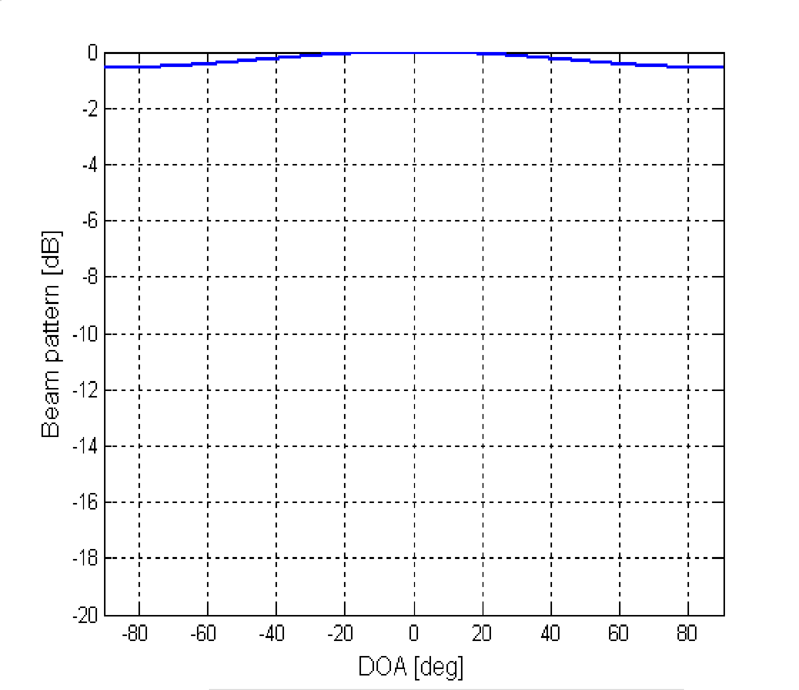
- To design the FIR filters one can:

1. to find the weighting windows providing the desired beam pattern at different frequency values
2. for each sensor, to use the sequence of the weight coefficients as the frequency response of the FIR filter connected to such a sensor
3. to move from the frequency response of the filter to its taps, representing the impulse response

Windowing

Point no. 1: to find the weighting windows providing the desired beam pattern at different frequency values

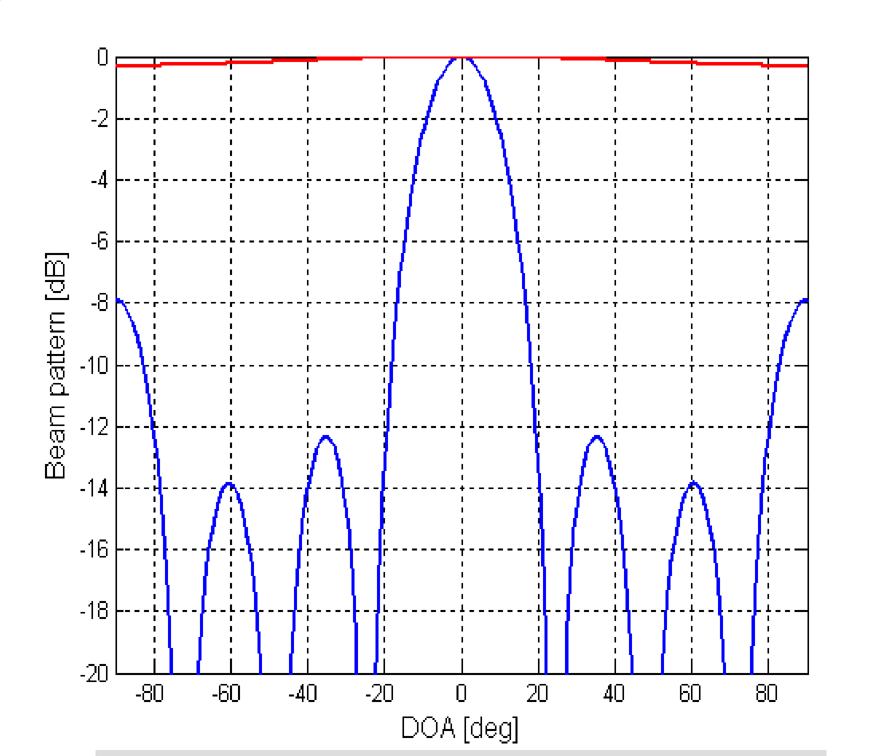
- The lowest frequencies are the most difficult
- Considering $f = 500$ Hz, the uniform window produces a useless beam pattern
- All the typical weighting windows enlarge the main lobe, reducing the array directivity
- We need **a window that increases the directivity** ⇒ **<u>superdirective arrays</u>**



Directivity = 0.2 dB

Superdirective arrays (1)

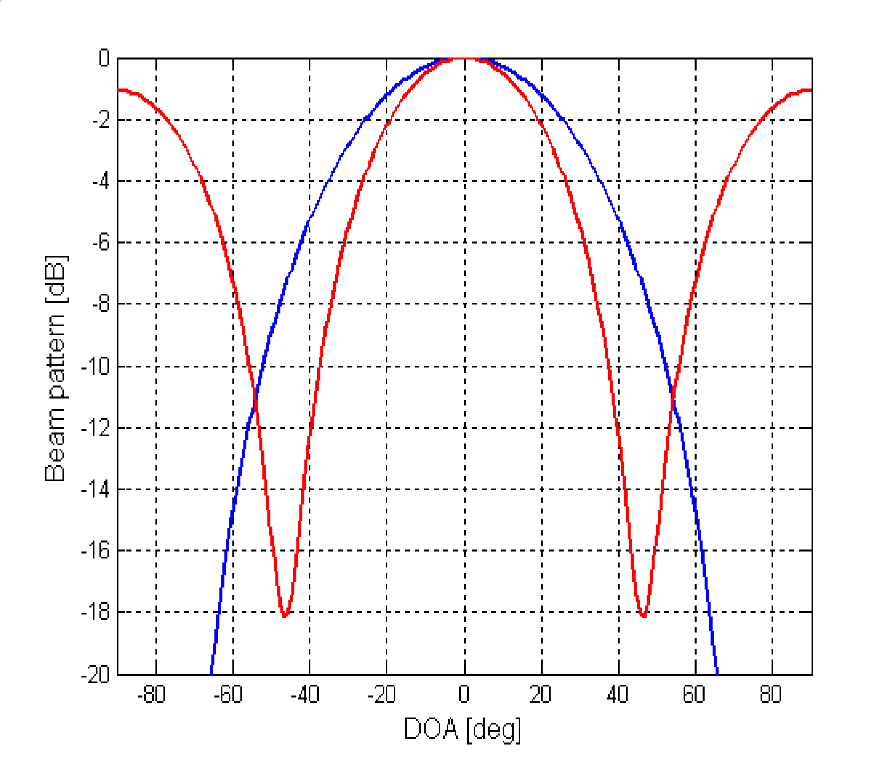
- An increase in directivity is obtained at the cost of a low tolerance with respect to random fluctuations
- The weighting window shows sign jumps
- **Maximum directivity array**: the window is computed by a matrix equation → the beam pattern (**blue line**) is impressive
- A Gaussian, multiplicative gain fluctuation is applied to each sensor, with mean = 1 and std. deviation = 0.1 → the beam pattern (**red line**) becomes useless



Directivity = 7.0 dB → 0.1 dB

Superdirective arrays (2)

- **Constrained directivity maximization**: a reduction in directivity is exchanged for an increase in robustness → the beam pattern (**blue line**) is nice
- The exchange can be tuned by a scalar coefficient inside the matrix equation
- After the random fluctuations the directivity is similar, the beam pattern (**red line**) shows an irregular shape

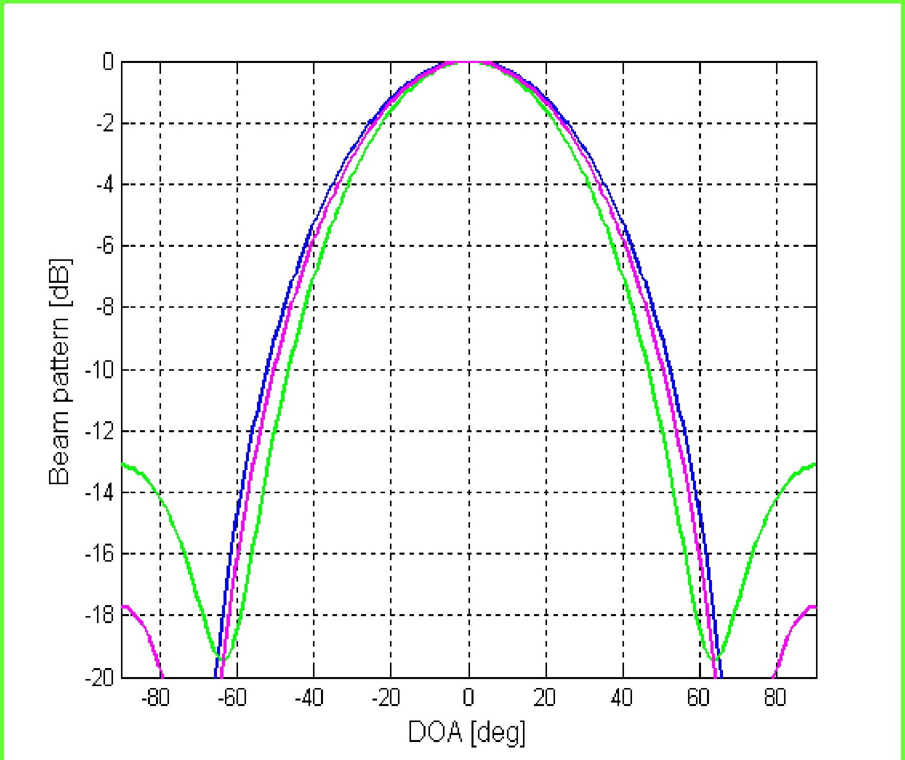


Directivity = 2.9 dB → 3.4 dB

Windows vs. frequency (1)

- Repeating the **constrained directivity maximization** at different frequency values one obtains window that produces very similar beam patterns:
- f = 500 Hz → **blue line**
- f = 1000 Hz → **magenta line**
- f = 1500 Hz → **green line**

- **1st problem:** the tuning process that allows to obtain similar beam patterns is a difficult and repetitive procedure



Windows vs. frequency (2)

- **2nd problem:** the frequency response of a sensor could change sign over frequency, e.g., sensor no. 6
- This fact inhibits to synthesize the taps of the FIR filter

Sensor no.	500 Hz	1000 Hz	1500 Hz	Sign
1	5.1644	1.3941	0.7454	+
2	-1.2909	-0.2562	-0.0737	-
3	-2.0118	-0.3908	-0.1024	-
4	-2.1574	-0.4005	-0.0867	-
5	-1.7280	-0.2869	-0.0304	-
6	-0.7294	-0.0560	0.0601	±
7	0.8274	0.2822	0.1767	+
8	2.9257	0.7140	0.3108	+

Desired beam pattern

- To overcome the problems of traditional methods in designing a wide-band superdirective arrays, the author proposed an novel approach:

  S. Repetto, A. Trucco, "A Stochastic Approach for the Apodization of Very Short Arrays," *Ultrasonics*, vol. 42, no. 1-9, pp. 425-429, April 2004.

- The aim is to synthesize a window providing a beam pattern that is similar to a desired one:

$$\min_{\mathbf{x}} \left\| \mathbf{A}\mathbf{x} - \mathbf{b} \right\|$$

x = weighting window

Ax = beam pattern, linear scale

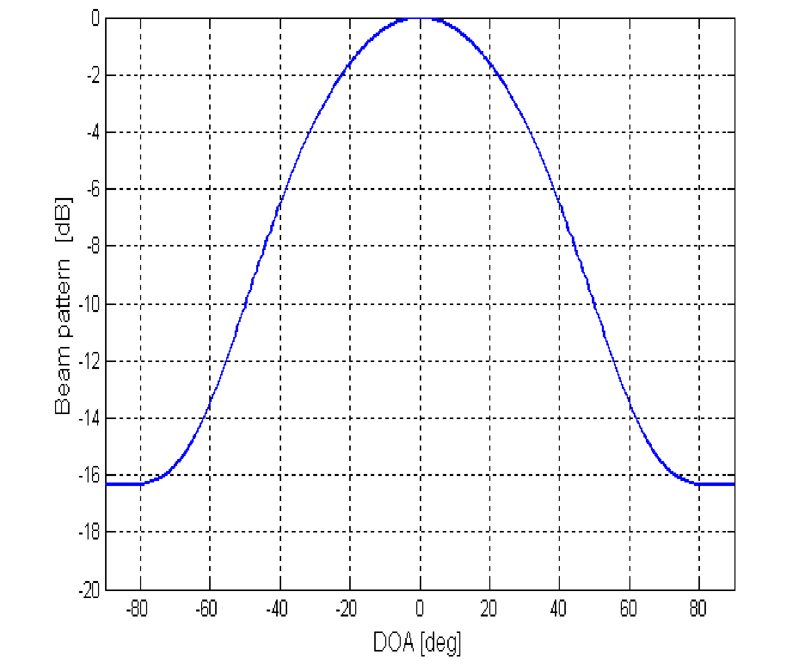
b = desired beam pattern

- Solution in the least-squares sense: $\bar{\mathbf{x}} = \left(\mathbf{A}^{H}\mathbf{A}\right)^{-1}\mathbf{A}^{H}\mathbf{b}$

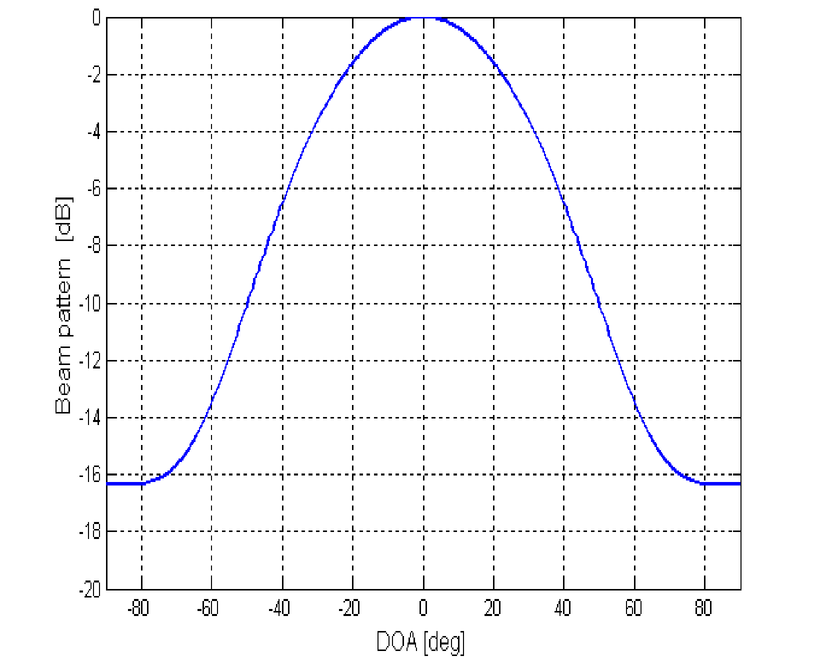
Least-squares solution

- At $f = 500$ Hz, the least-squares solution is impressive
- Unfortunately, it is very sensitive to random fluctuations: absolutely **useless in practical system**

Desired beam pattern



Obtained beam pattern



Simulated annealing approach (1)

- A different approach, based on a stochastic optimization technique followed by a local descent method for unconstrained minimization, has been attempted
- Definition of an energy function $E(\mathbf{x})$ to be minimized:

$$E(\mathbf{x}) = \left\| \mathrm{diag}\left(\mathbf{A}\mathbf{x}\mathbf{x}^{\mathrm{H}}\mathbf{A}^{\mathrm{H}}\right) - \mathrm{diag}\left(\mathbf{b}\mathbf{b}^{\mathrm{H}}\right) \right\|$$

$\mathbf{x}$ = weighting window

$\mathrm{diag}(\mathbf{A}\mathbf{x}\mathbf{x}^{\mathrm{H}}\mathbf{A}^{\mathrm{H}})$ = beam power pattern

$\mathrm{diag}(\mathbf{b}\mathbf{b}^{\mathrm{H}})$ = desired beam power pattern

- Although the function $E(\mathbf{x})$ is conceptually similar to the previous one, now the function has many local minima

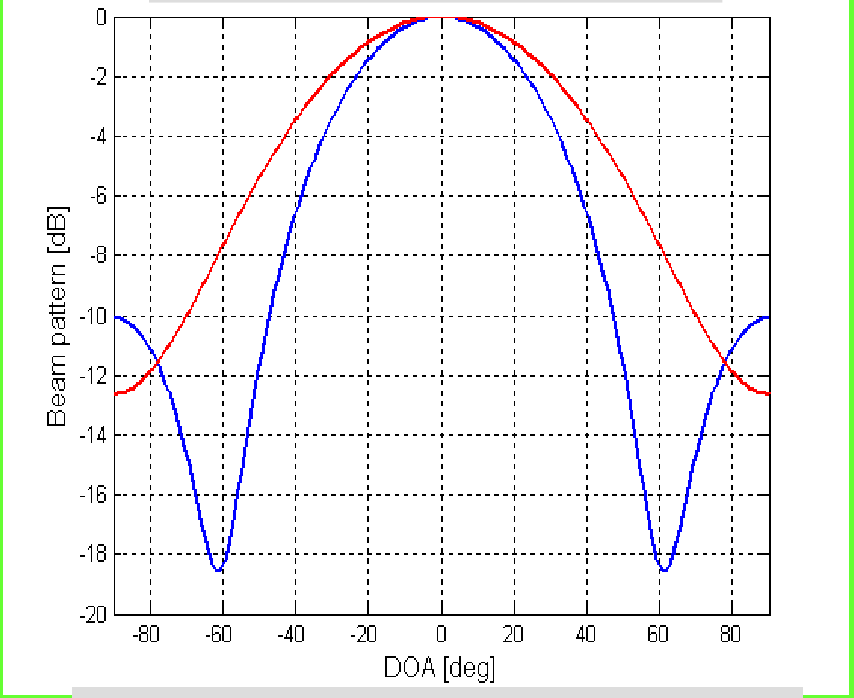
Simulated annealing approach (2)

- It can be expected that some of the minima are more stable than the least-squares solution
- Simulated annealing (SA) reaches the final solution by a sequence of little approximations: the final solution is very frequently stable
- If the global minimum is unstable, SA will probably not succeed in finding the global minimum; it will stop inside the basin of a stable local minimum with an energy value close to that of the global minimum

Simulated annealing approach (3)

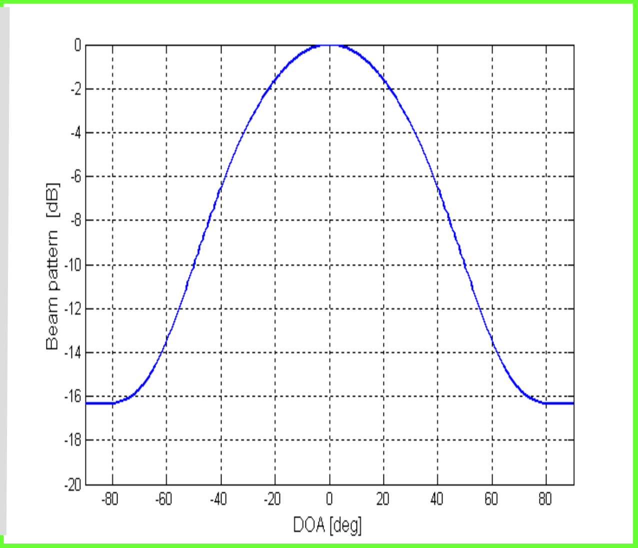
- At f = 500 Hz, sharp similarity with the desired beam pattern, especially in the upper part of the main lobe
- After the random fluctuations, the directivity is lower, the beam pattern (**red line**) shows a regular shape

Obtained beam pattern



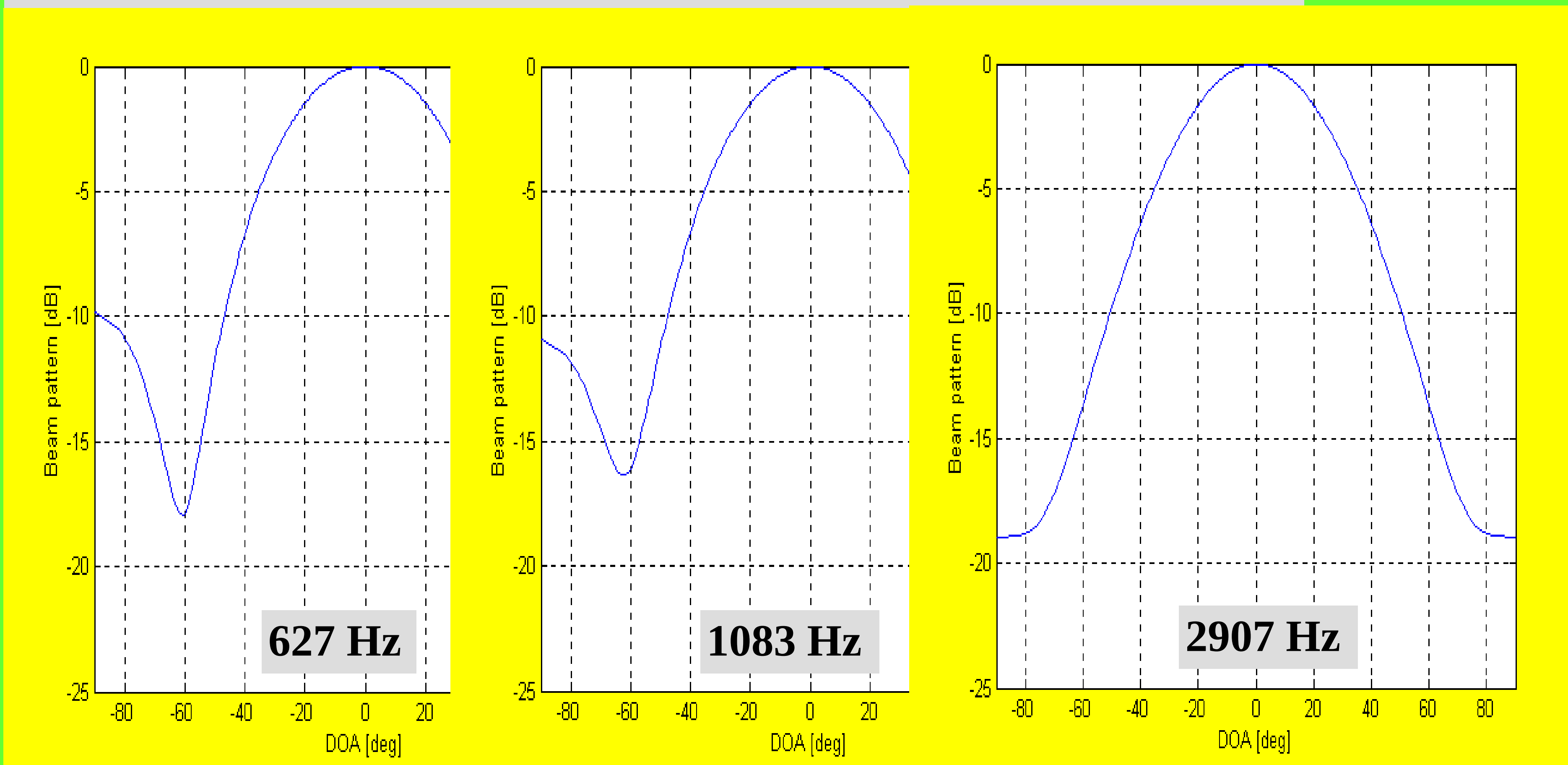
Directivity = 3.2 dB → 2.2 dB

Desired beam pattern



SA: windows vs. frequency (1)

Repeating the **SA approach** at different frequency values, with the same desired beam pattern, one obtains windows that produce quite similar beam patterns



SA: windows vs. frequency (2)

Point no. 2: for each sensor, to use the sequence of the weight coefficients as the frequency response of the FIR filter connected to such a sensor

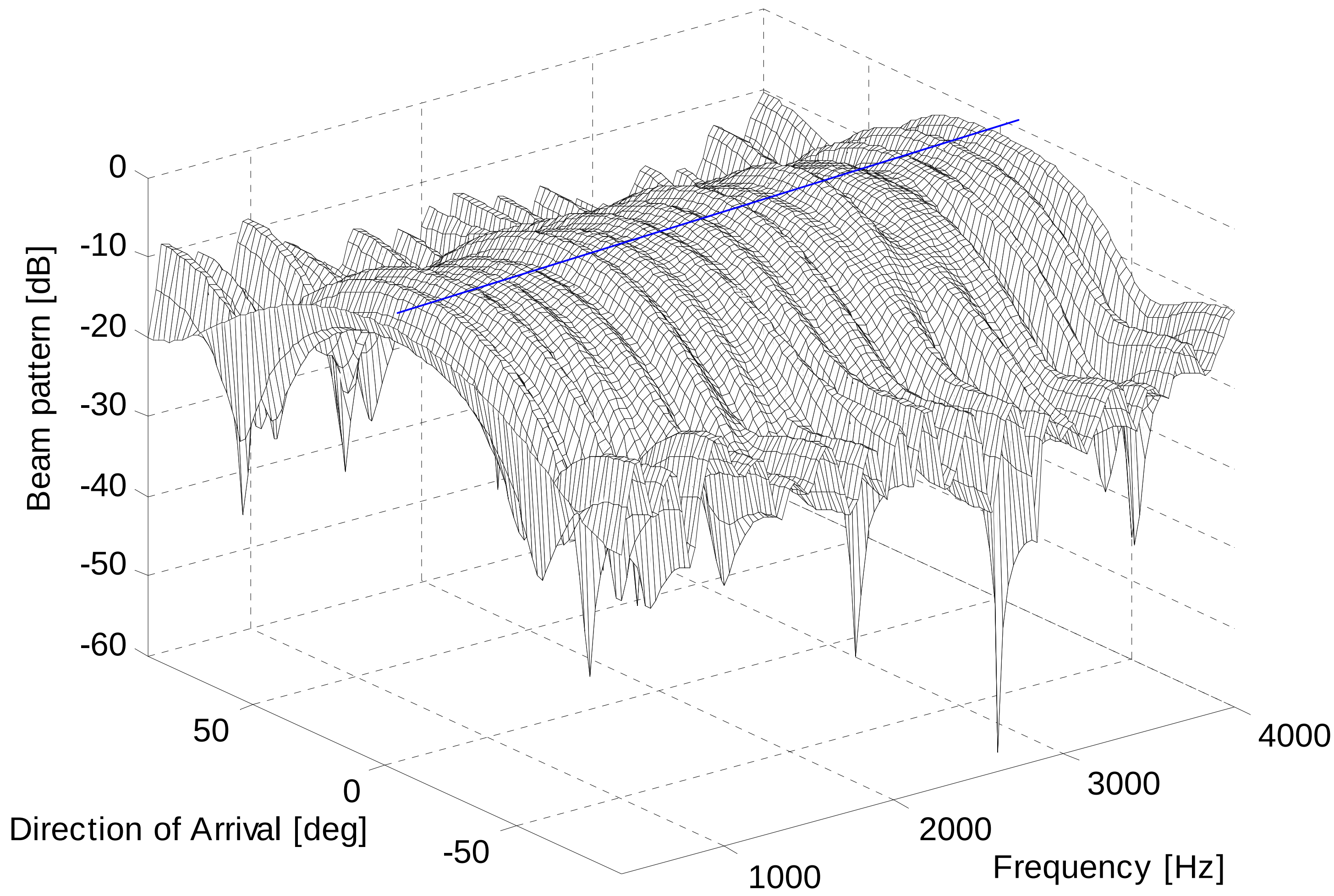
- 28 weighting windows at 28 frequency values are synthesized by the SA approach
- The first one is the window at the lowest frequency value (the most difficult one!)
- At the other frequency values, SA allows to force the sign of the weight associated to a given sensor to be equal to the sign obtained at the lowest frequency for that sensor.
- Now, the point no. 2 of the procedure is satisfied

Parks-McClellan

Point no. 3: to move from the frequency response of the filter to its taps, representing the impulse response

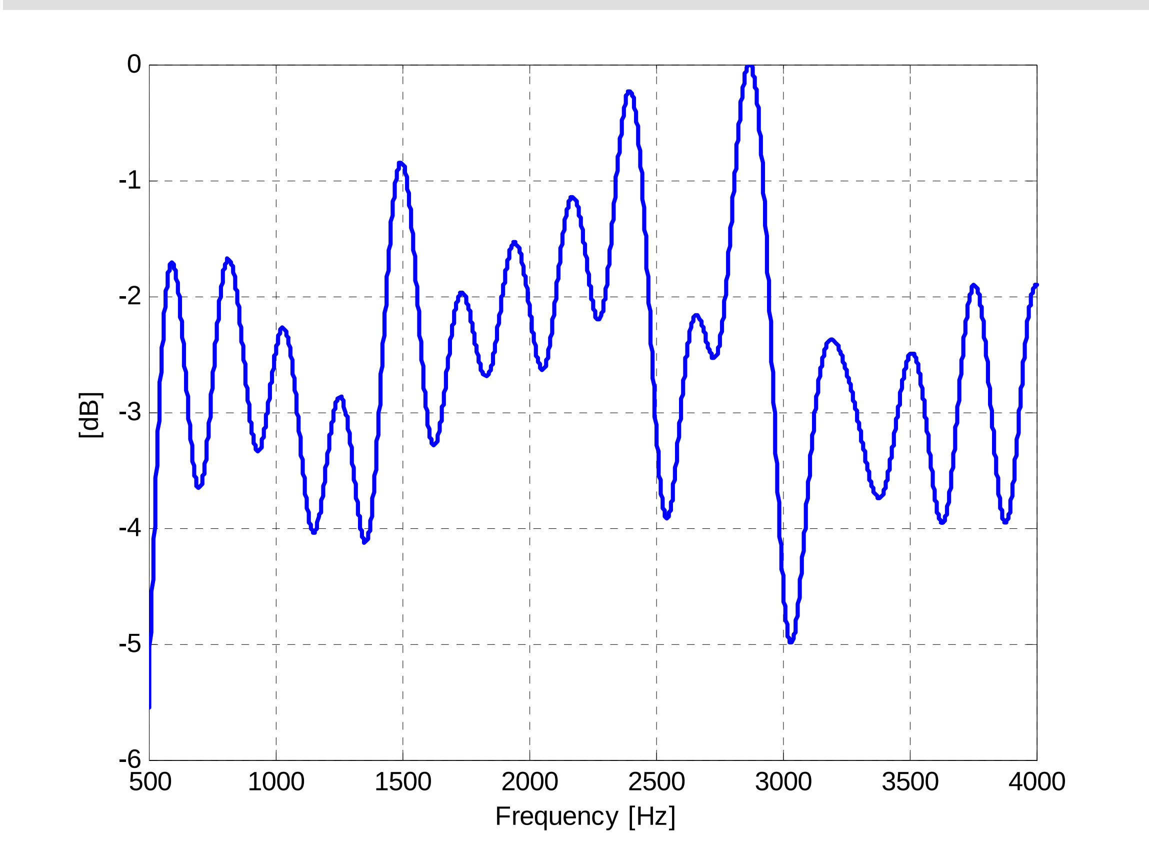
- The algorithm of Parks-McClellan is used to design the taps of the filters, applying the algorithm at each sensor
  - The Parks-McClellan algorithm uses the Remez exchange algorithm and the Chebyshev approximation theory to design filters with an optimal fit between the desired and the actual frequency responses
  - Filters designed in this way show a linear phase and an equiripple behaviour in their frequency responses
- By starting from the 28 weighting windows, 8 FIR filters of 70^{th} order have been synthesized (sampling frequency = 8 kHz)

Wide-band beam pattern (1)



Wide-band beam pattern (2)

Slice of the wide-band beam pattern at a direction of sound arrival equal to 0°, i.e., broadside.



Although, from a macroscopic point of view, a frequency-invariant shape has been obtained over three octaves, a 5 dB ripple is present, despite the accurate design (28 frequency bands)

Direct taps synthesis (1)

- The beam pattern over frequency is directly linked to the filter taps:

$$BP(\theta, f; \mathbf{Q}) = \left| \sum_{i=0}^{N-1} \sum_{l=0}^{K-1} Q_{i,l} \cdot e^{-j2\pi f\left[i \cdot d \sin\theta / c + lT\right]} \right|$$

K-1 = filters' order

θ = direction of arrival

$Q_{i,l}$ = l-th tap coefficient of filter i

$\mathbf{Q}$ = matrix of the taps

- The SA approach can be used to directly synthesize filter taps that are able to produce a desired beam pattern for a FIB

Direct taps synthesis (2)

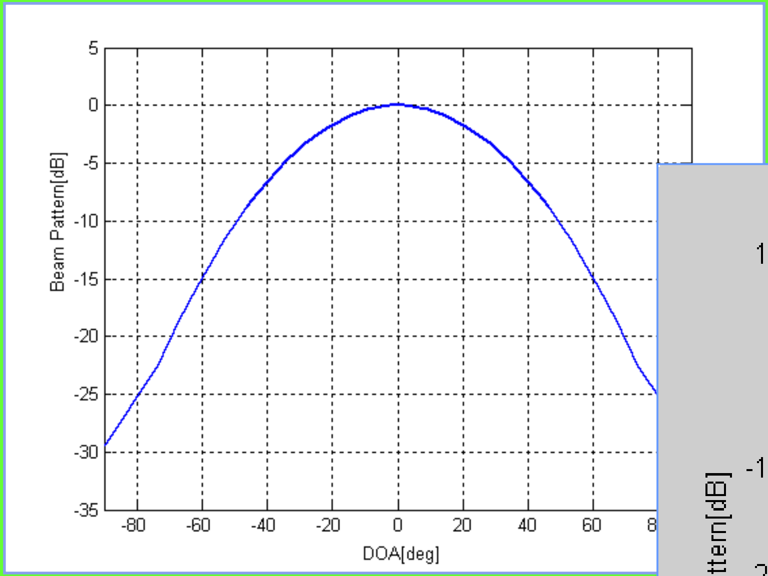
- A new energy function can be defined as follows:

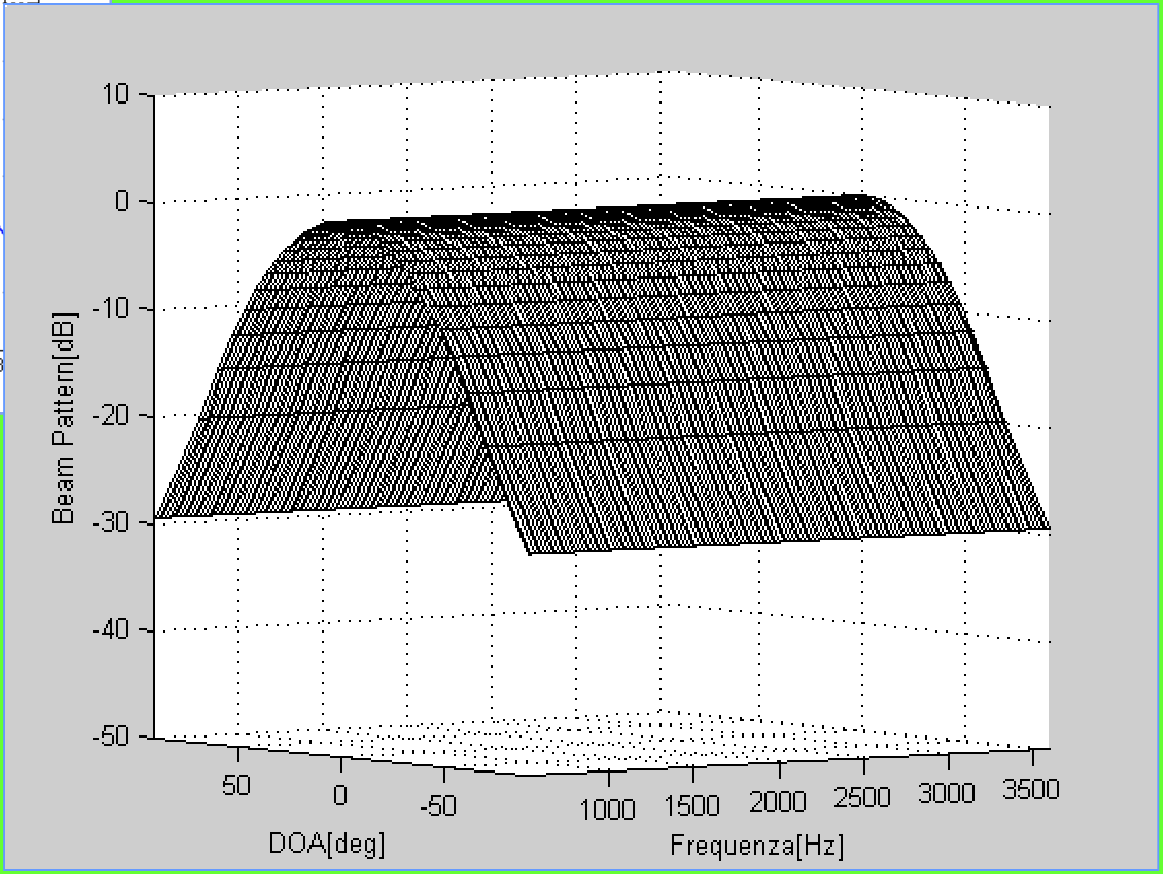
$$E(\mathbf{Q}) = \int\int \left| BP(\theta, f; \mathbf{Q}) - BP_{des}(\theta, f) \right| df\ d\theta$$

$BP_{des}(.)$ = desired beam pattern

- To attain a successful solution by using SA, the application of some tricks.

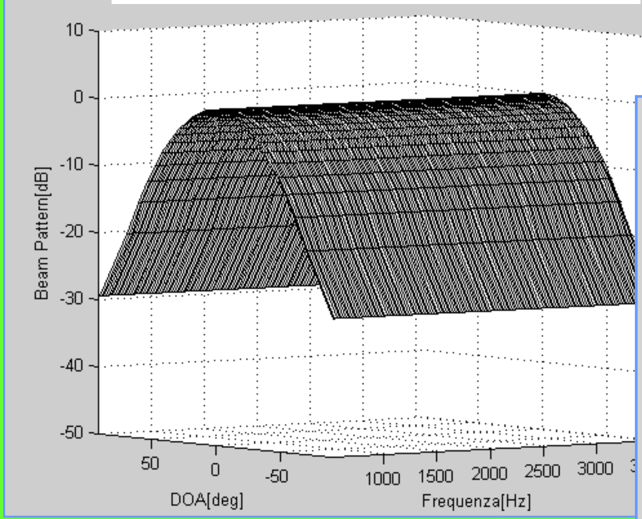
Desired beam pattern

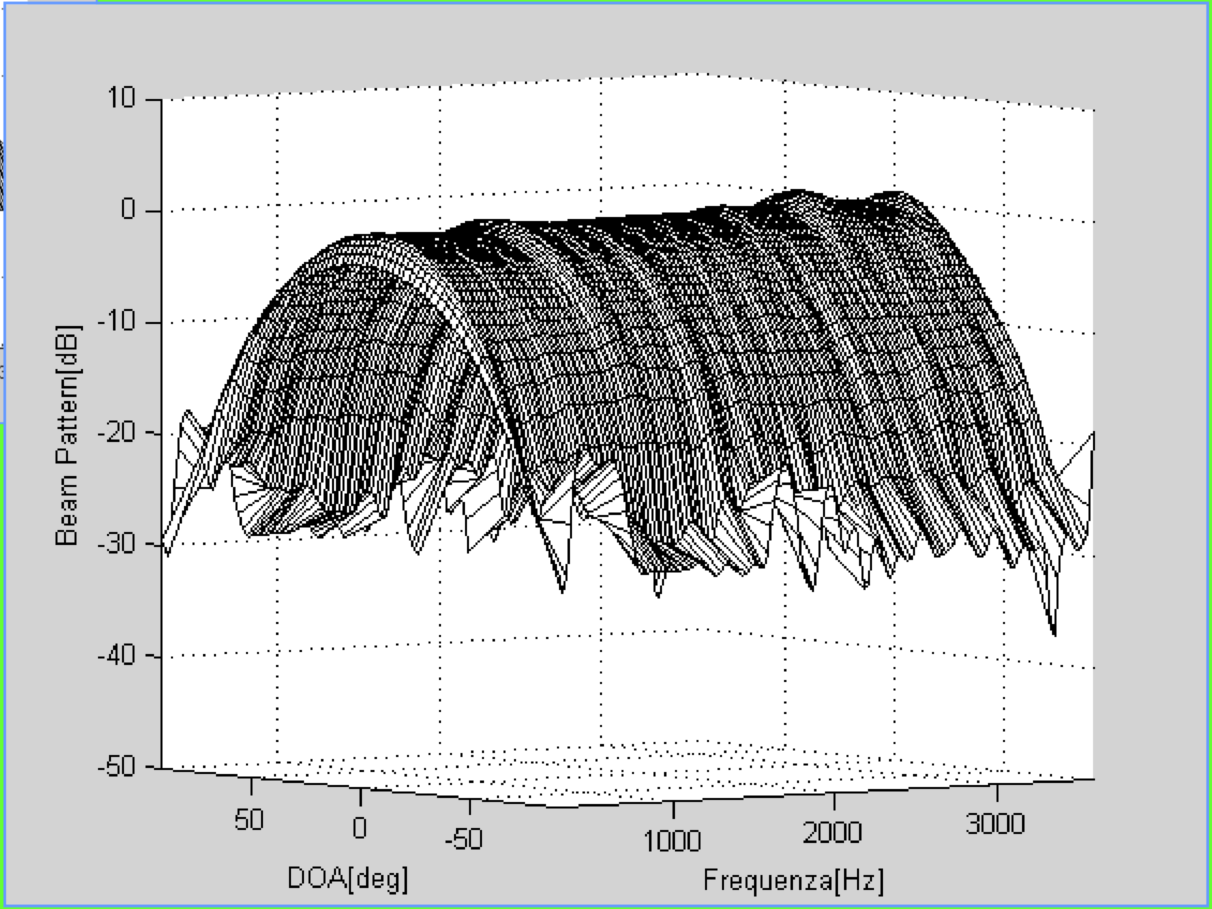




Obtained beam pattern (1)

Desired beam pattern



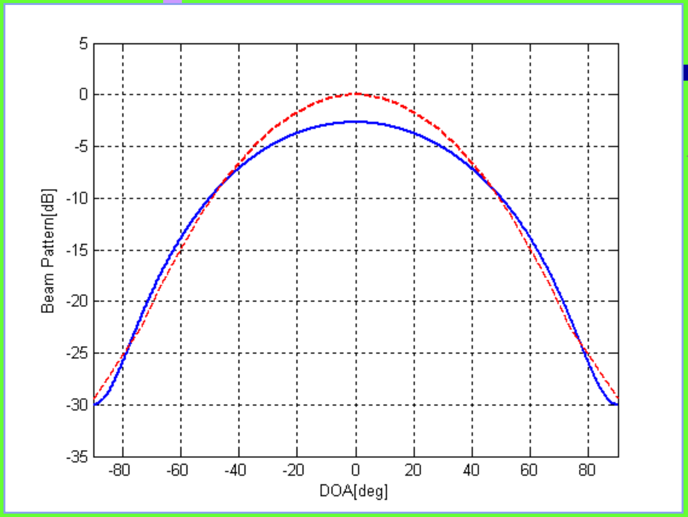


<u>Frequency range</u>: 300÷3600 Hz

Filters' order: 72

Sampling frequency: 8 kHz

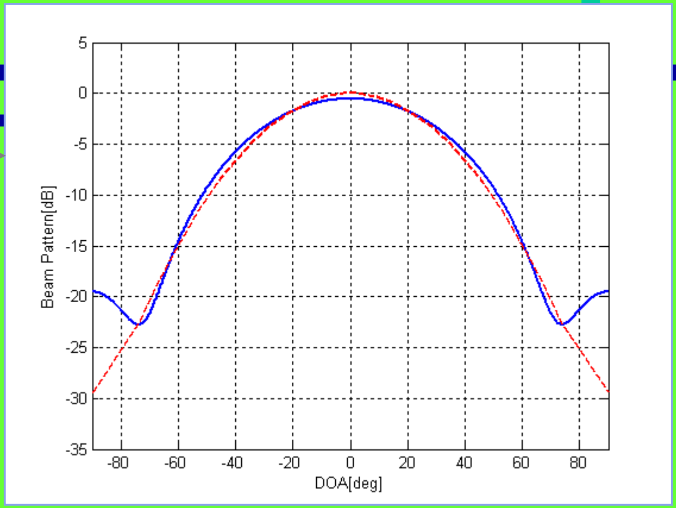
Slices



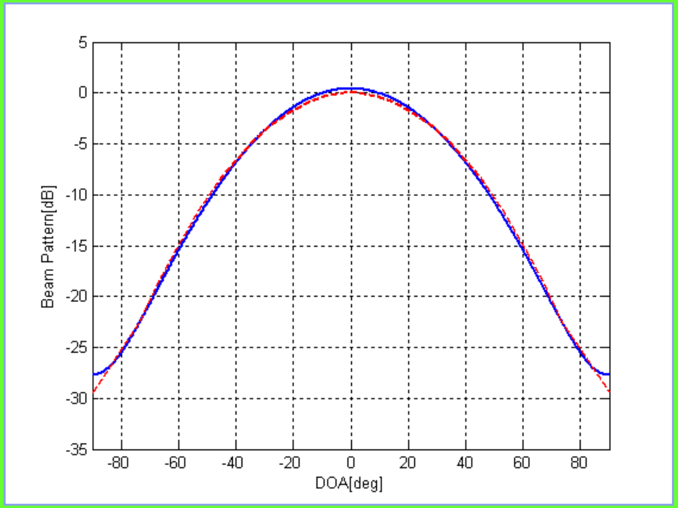
300 Hz

Desired beam pattern

Obtained beam pattern



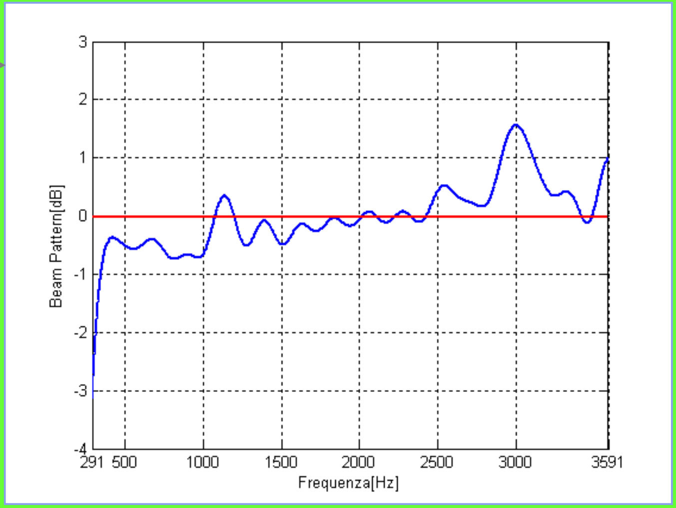
520 Hz



2500 Hz

Mean value

Obtained beam pattern



0°

Conclusions

- Sensor arrays using tapped-delay lines provide very interesting spatial filtering capability:
  - also if the aperture is much shorter than the longest wavelength (0.14λ)
  - with a beam pattern that is constant over a wide range of frequencies (3 octaves)
- The approach based on the *desired beam pattern*, carried out by SA minimization, is very relevant in this context
- The direct synthesis of the taps seems to produce the best results

Future work: bioacoustics perspective

- To compare performances of the designed array with those of selected natural bioacoustics systems
- To check for similarity in the signal processing structure between the array case and animals
- To improve the designed array (possibly by integrating concepts coming from natural systems) and use it as a building block in emulating complex bioacoustics systems

Appendix 3i

John Rees

Collaborative Research

John Rees

British Geological Survey
Keyworth
Nottingham
NG12 5GG

RESEARCH COUNCILS UK Together in research

- Strategic partnership set up to champion science, engineering and technology
- Supported by the seven UK Research Councils
- These are working together to create a common framework for research, training and knowledge transfer in the UK.
- RCUK works alongside the office of science and technology
- Supports the UK’s best academic researchers
- Delivers the best investment for society

NATURAL ENVIRONMENT RESEARCH COUNCIL

MRC Medical Research Council

EPSRC

Basic Technology Research Programme

- Makes strategic investments
- Develops truly innovative cutting edge technology
- Offers the prospect of making significant scientific advances
- Research supported by this programme of very high quality
- Innovative approaches are needed to address the technical challenges

“Success will undoubtedly bring the opportunity of changing the landscape of research knowledge, and provide opportunities for commercial exploitation”.

Basic Technology Research Programme

Towards an acoustic spectrometer (2003)

Biomimetric acoustic sensing: applications in imaging (2004)

John Rees (British Geological Survey)
Laurie Linnett (Research Associate, British Geological Survey)
Gordon Hayward (Ultrasound Engineering, Strathclyde)
Mike Lovell (Petrophysics, Leicester)
Norman McDicken (Medical Physics and Medical Engineering, Edinburgh)
Steve McLaughlin (Electronics and Electrical Engineering, Edinburgh)
Robert Allen (Institute of Sound and Vibration Research, Southampton)

Keep watching!

International cooperation

Summary

- UKRC and component councils main source of support in the UK
- Value in inter-disciplinary research
- UK scientists actively searching for collaboration
- Need for open forum
- Funding

Questions ?

Appendix 3j

Dean Waters

Humans and Sonar: sound, maps and senses

Dr Dean Waters

School of Biology

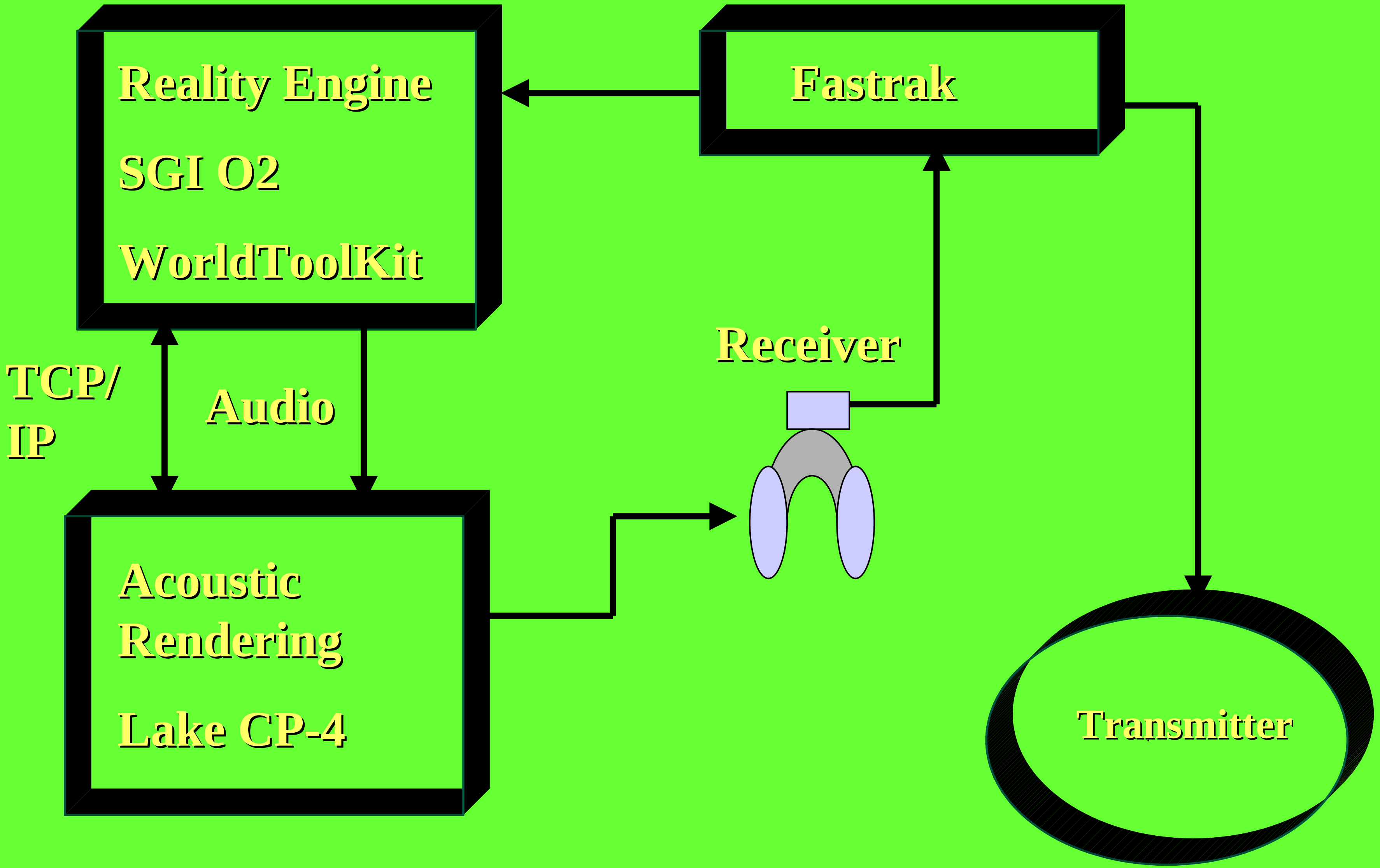
University of Leeds

UK

1. **Sound maps and real maps**
2. **Assistive technologies**

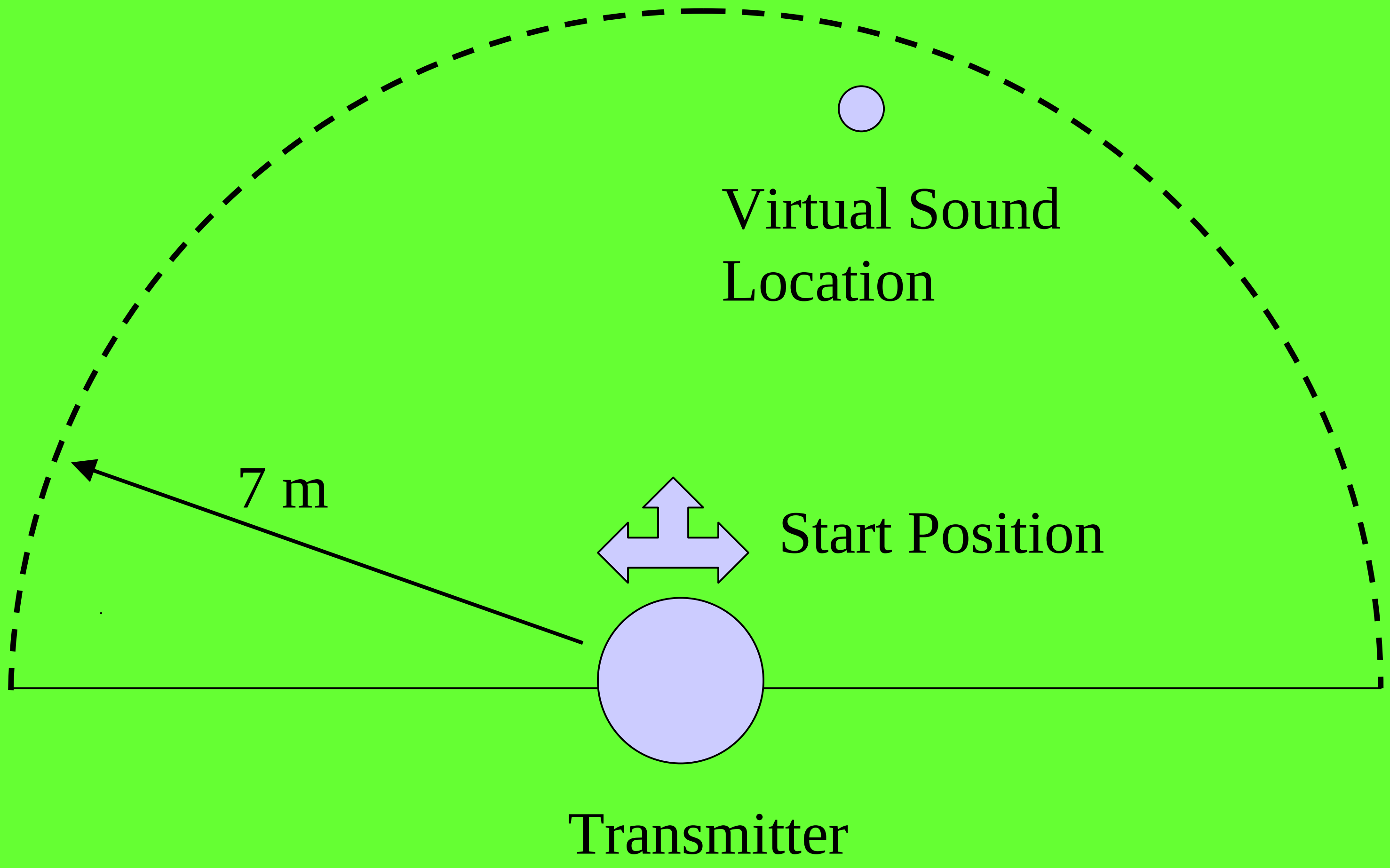
Question: can we use sonar to describe the world around us in a meaningful way?

- Technical limitations
  - Speed of sound
  - Sound ‘spatialisation’
- Can we use it in more abstract ways?


Reality Engine
SGI O2
WorldToolKit
Fastrak
Receiver
TCP/
IP
Audio
Acoustic
Rendering
Lake CP-4
Transmitter

Experimental Arena

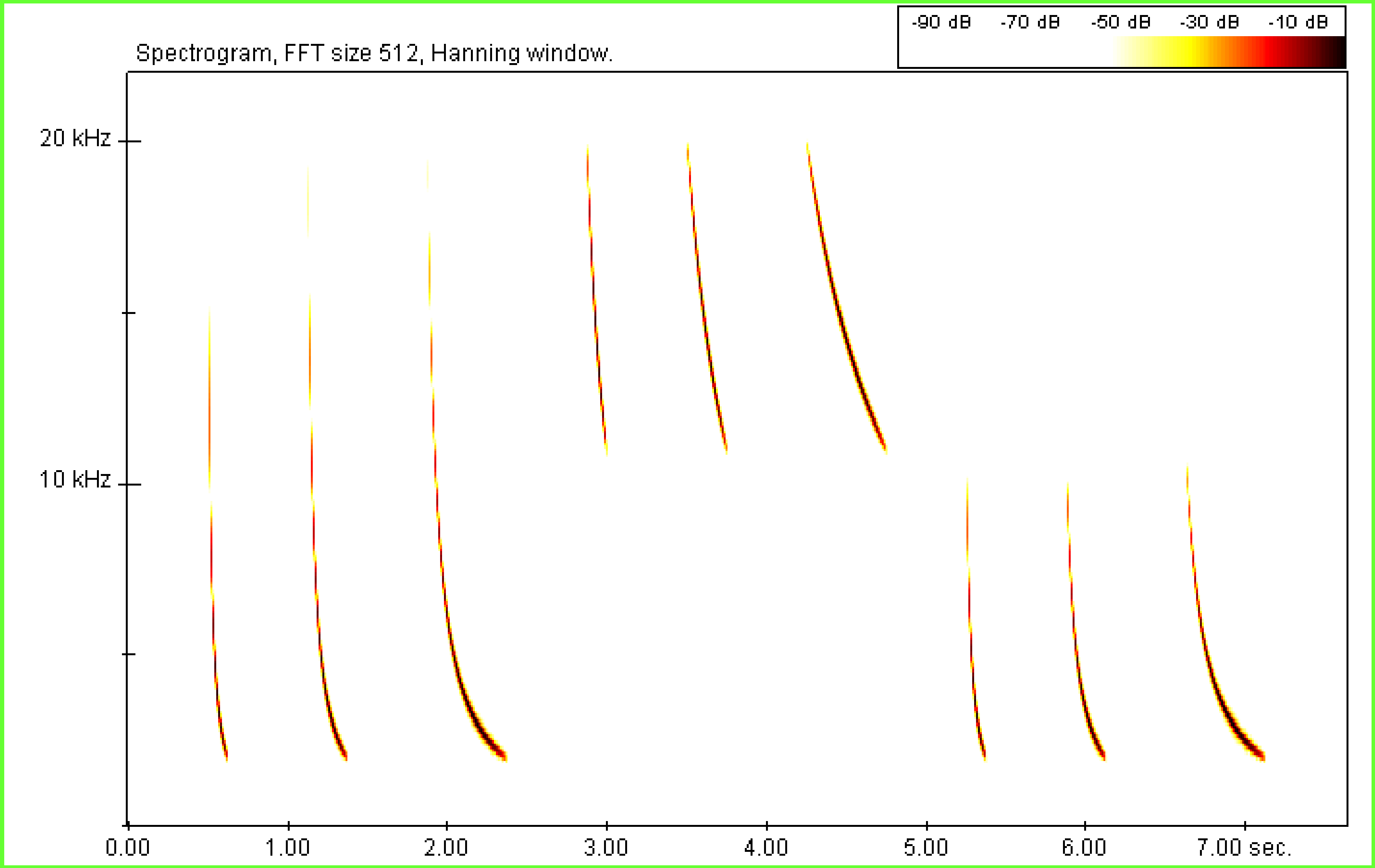
Experimental Setup



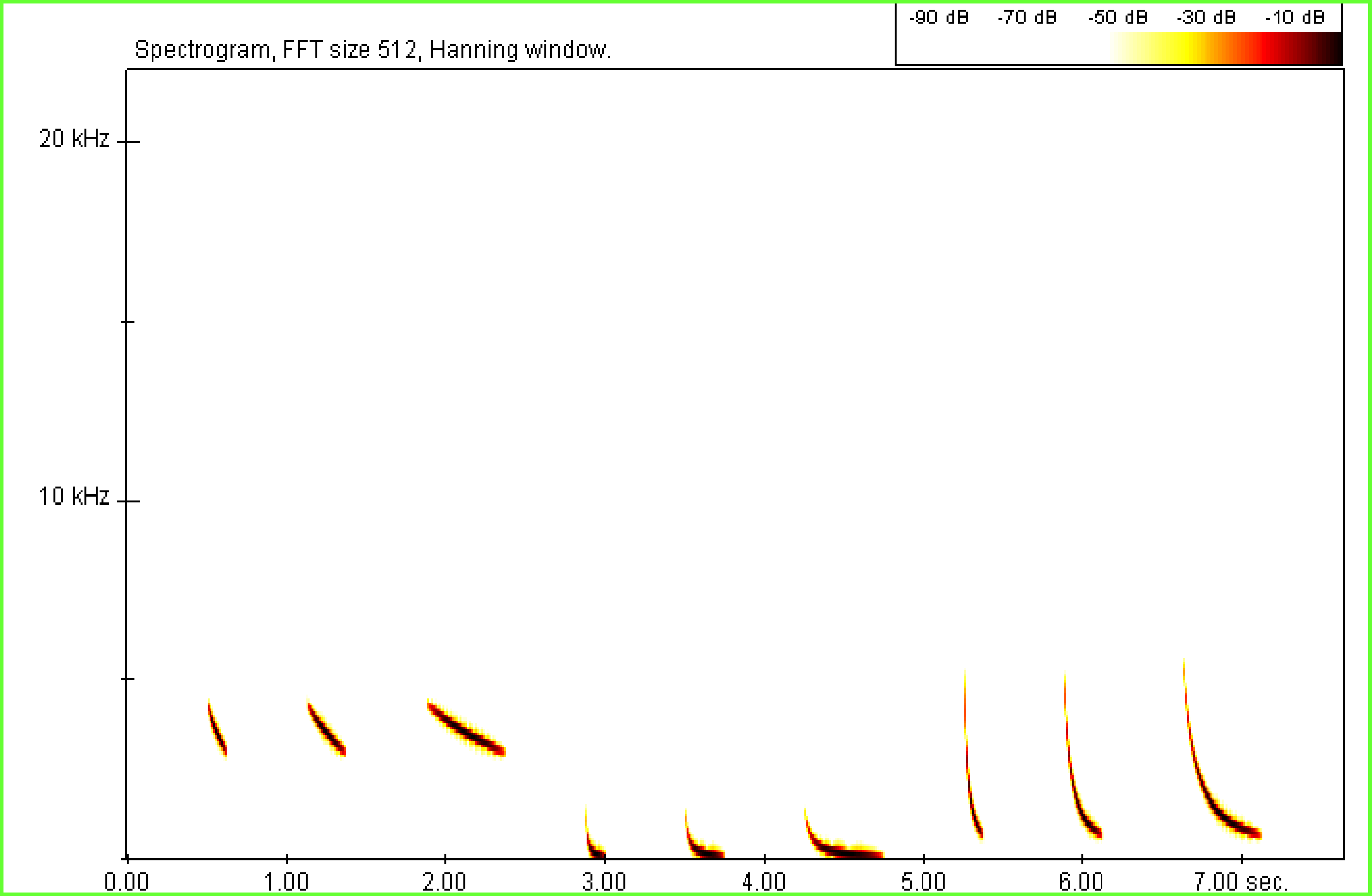
Mode of Operation

- Users head position and orientation is encoded
- Position relative to virtual sound position is calculated
- ‘Outgoing’ pulse is centered on the users head as a reference
- Time delay to echo is calculated using 8.5 ms^{-1} as the speed of sound
- At calculated time interval, echo sound is output
- Echo sound is rendered at the virtual sound location

Broadband Set of Signals



Narrowband Set of Signals



Also Four Controls

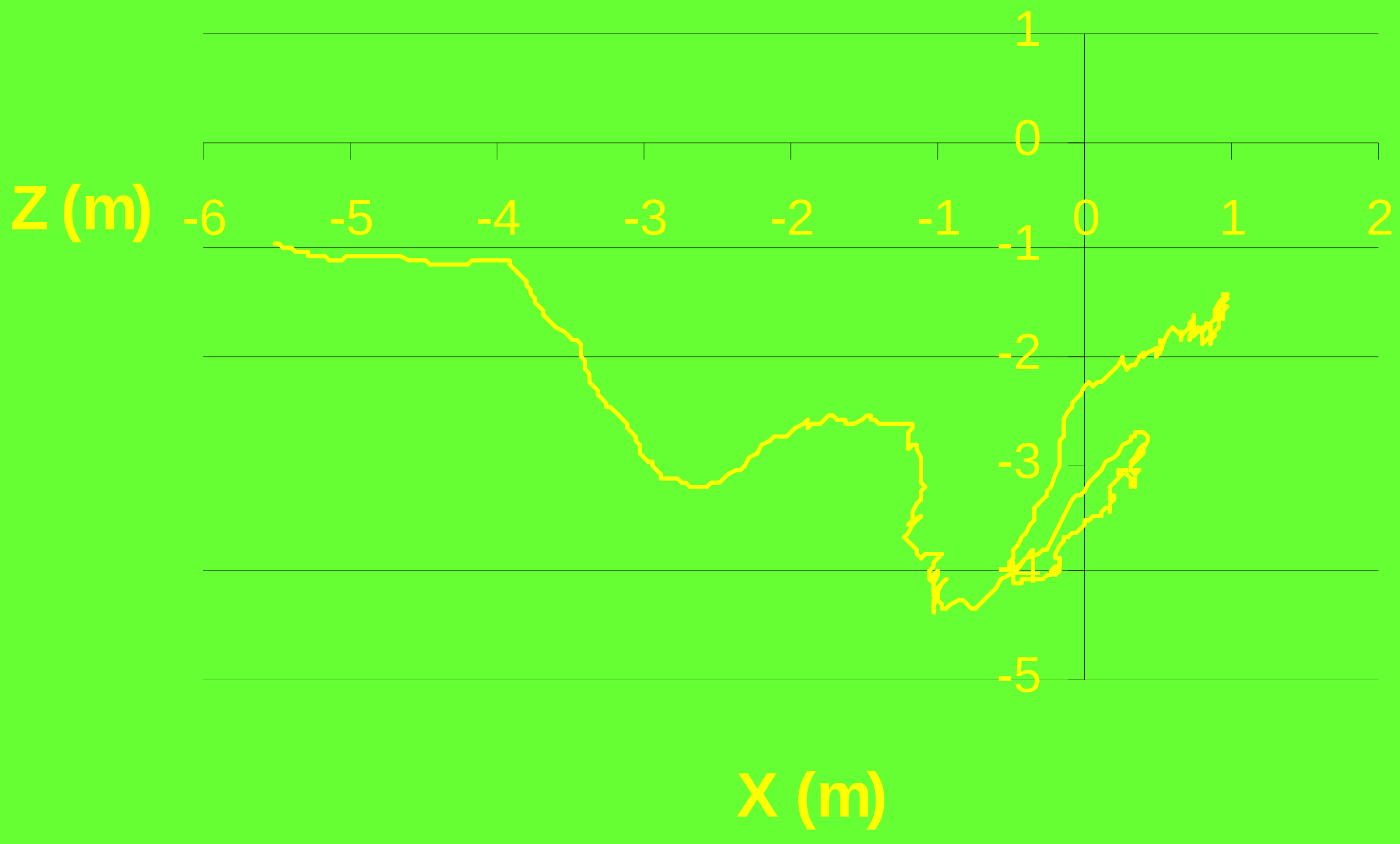
- White Noise at 125 ms, 250 ms and 500 ms duration
- Continuous broadband music

Experimental Procedure

- 22 Signals
- Signal presentation order is randomized
- The subject walks around the arena and a position is captured
- The position is used as the virtual sound position
- The subject must locate the sound within 30 seconds

An Accurate Localization

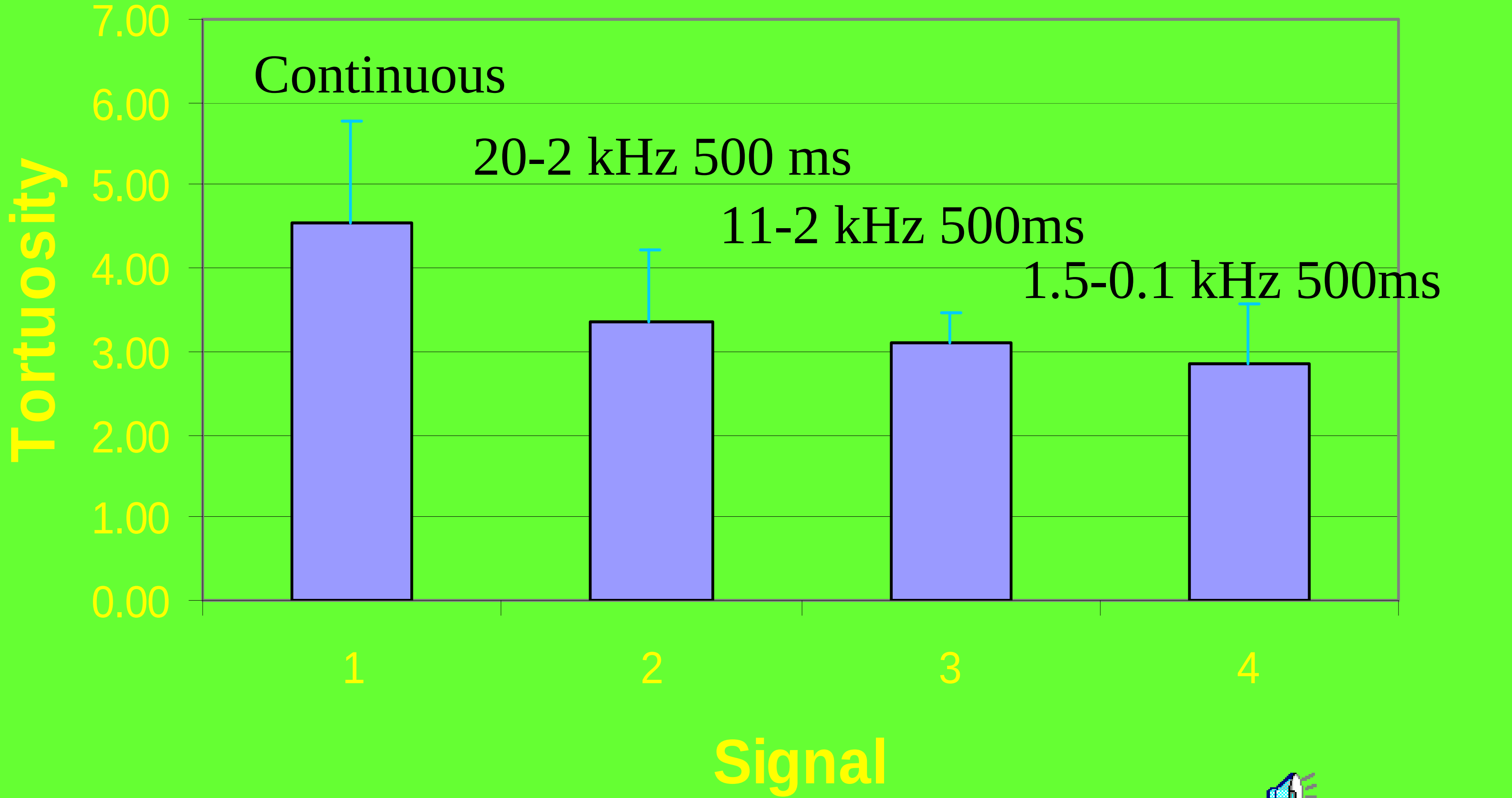
An Inaccurate Localization



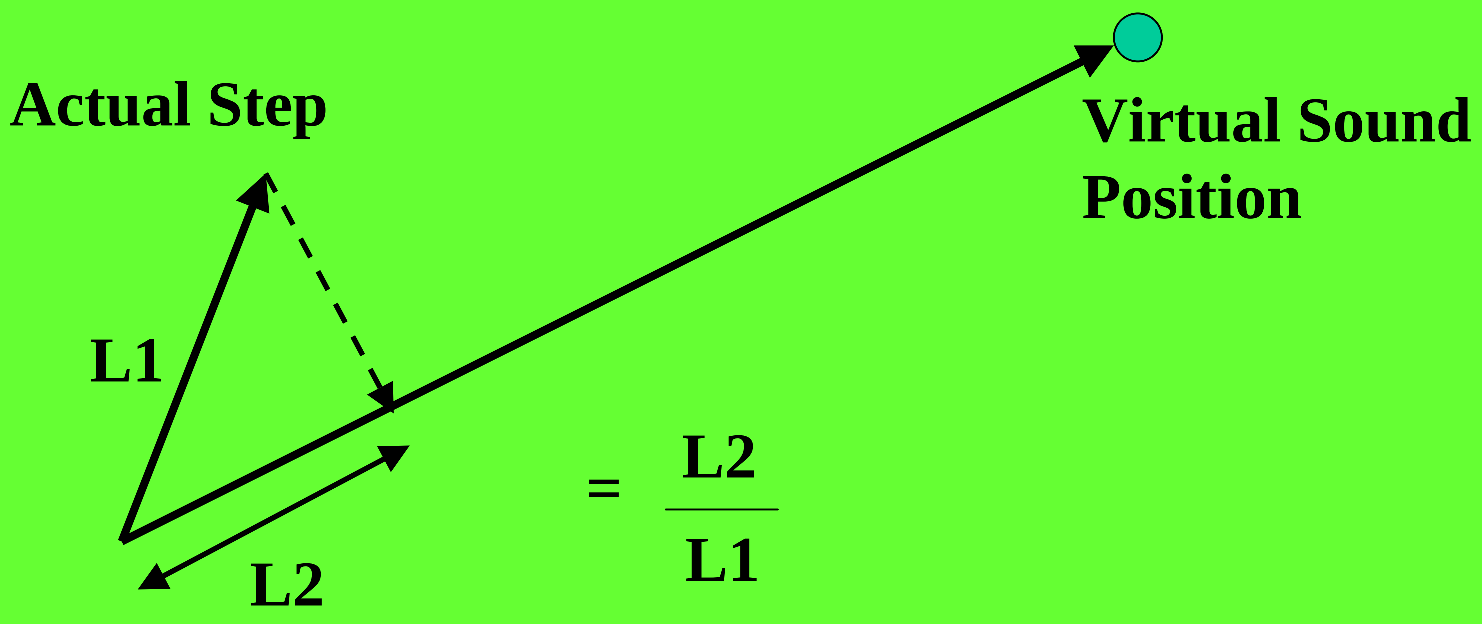
Localization Indices

$$\text{Tortuosity} = \frac{\text{Total Path Length}}{\text{Direct Path Length}}$$

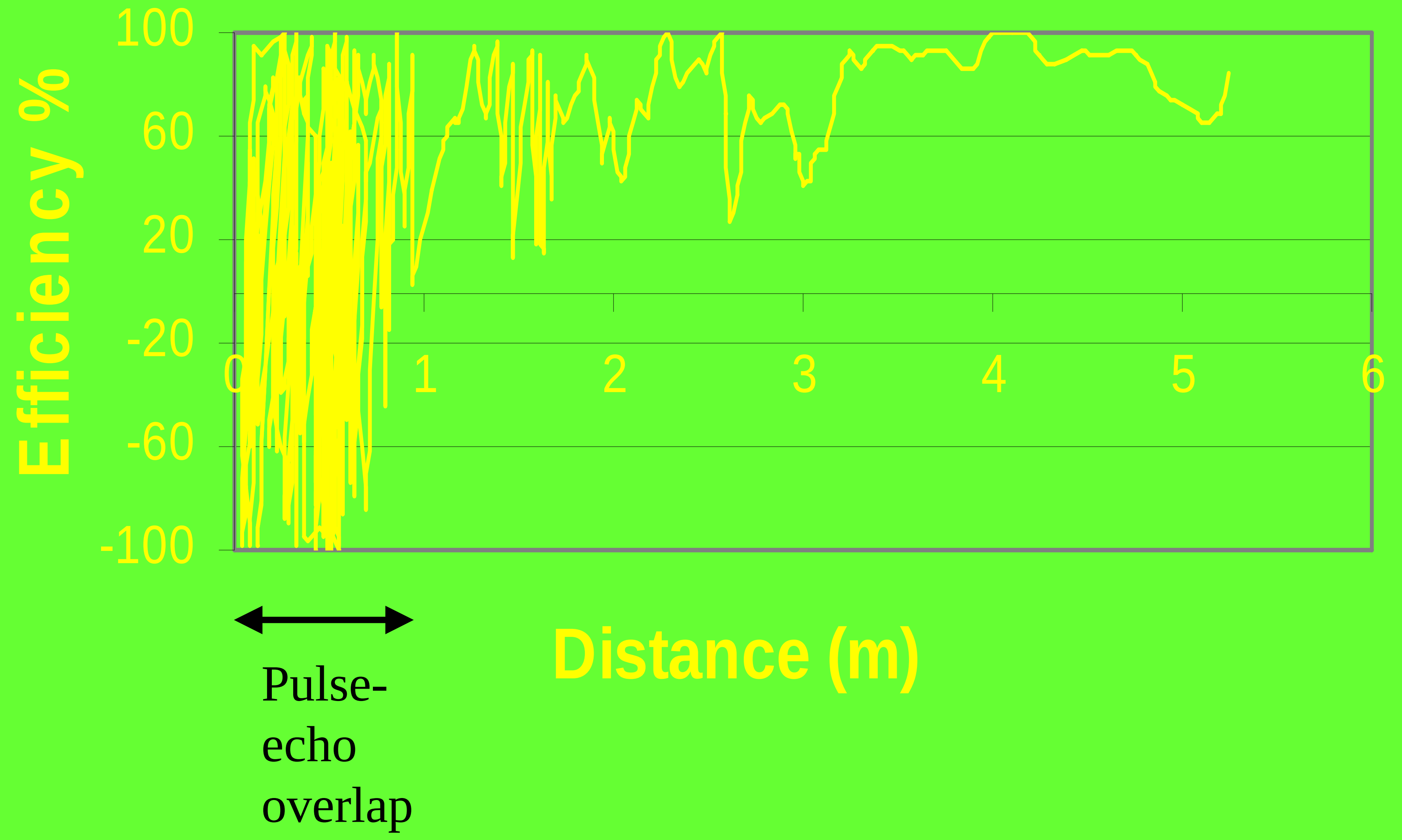
Tortuosity Results



Mean Effective Path



Localization with Distance



Results so far…….

- Sonar can provide a better localization tool in VR than continuous sound sources
- A 500 ms signal sweeping from 1.5-0.1 kHz is so far the best tested
- Pulse-echo overlap is a problem close to the target

Further Work

- To add user control for sound duration to avoid pulse-echo overlap problems.
- Add multiple targets.
- Implement audio-rendering applicable to any VR environment.

Helping the visually impaired

- Can we use bat sonar to help people with visual impairments?
- Use bat-like sonar to map the local environment
- Give that map to the user

…Recent electronic aids

Sonic Pathfinder
Aimed at wheelchair users
Ultrasound sensors
Audible Feedback
Price £900
Sold 226 devices

Nav Belt and ***Mini Guide***
Both ultrasound, both audible feedback, Mini Guide tactile also

One iteration of the ***LaserCane***
First introduced in the 1960's
Price £1800
To date sold 450 canes

Issues about information relay

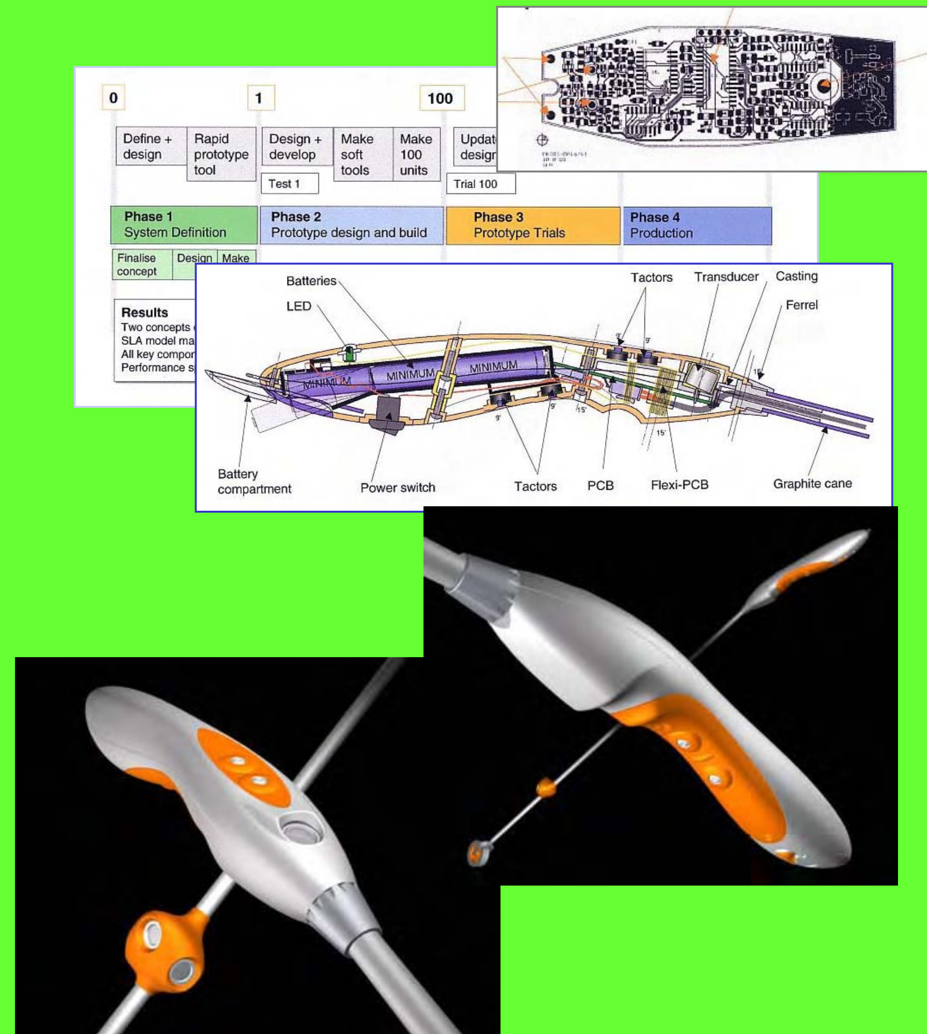
- Keep the audible channel clear for other navigational cues.
- Other sensory modalities such as touch have much lower available bandwidth.

First prototypes

- Used ultrasound to detect the distance of objects:
  - In front
  - Left
  - Right
  - Above
- Relay that ‘map’ to a tactile array in the handle
- The closer the object, the faster the vibration

The Ultracane

- 4 transducers
- Pulse-echo mode
- Distance relayed as vibrational frequency
- Non-linear map of range-frequency

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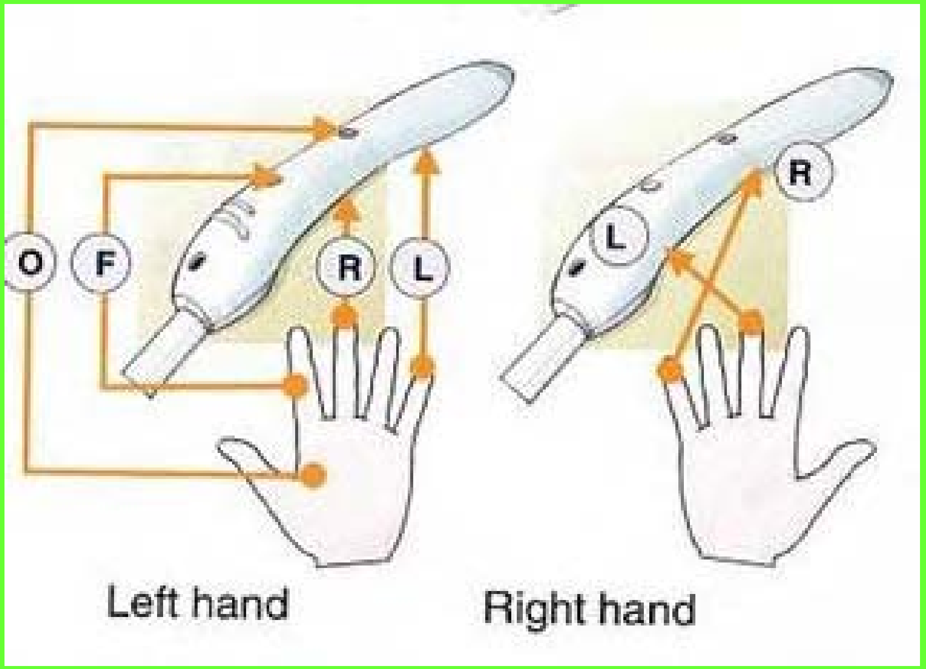
TEAS

Use issues

- A target is just a target – not possible to resolve what that target is.
- Too sensitive a device creates too many false positives.
- Still requires 'sweeping' to resolve target extent.

Designs for the future

- The bandwidth of tactile senses in the hand should be high enough for good resolution.
- Extraction of multiple reflection data and conversion to a space map is important.
- Relay of that map via tactile means is a challenge.



Appendix 3k

Les Atlas

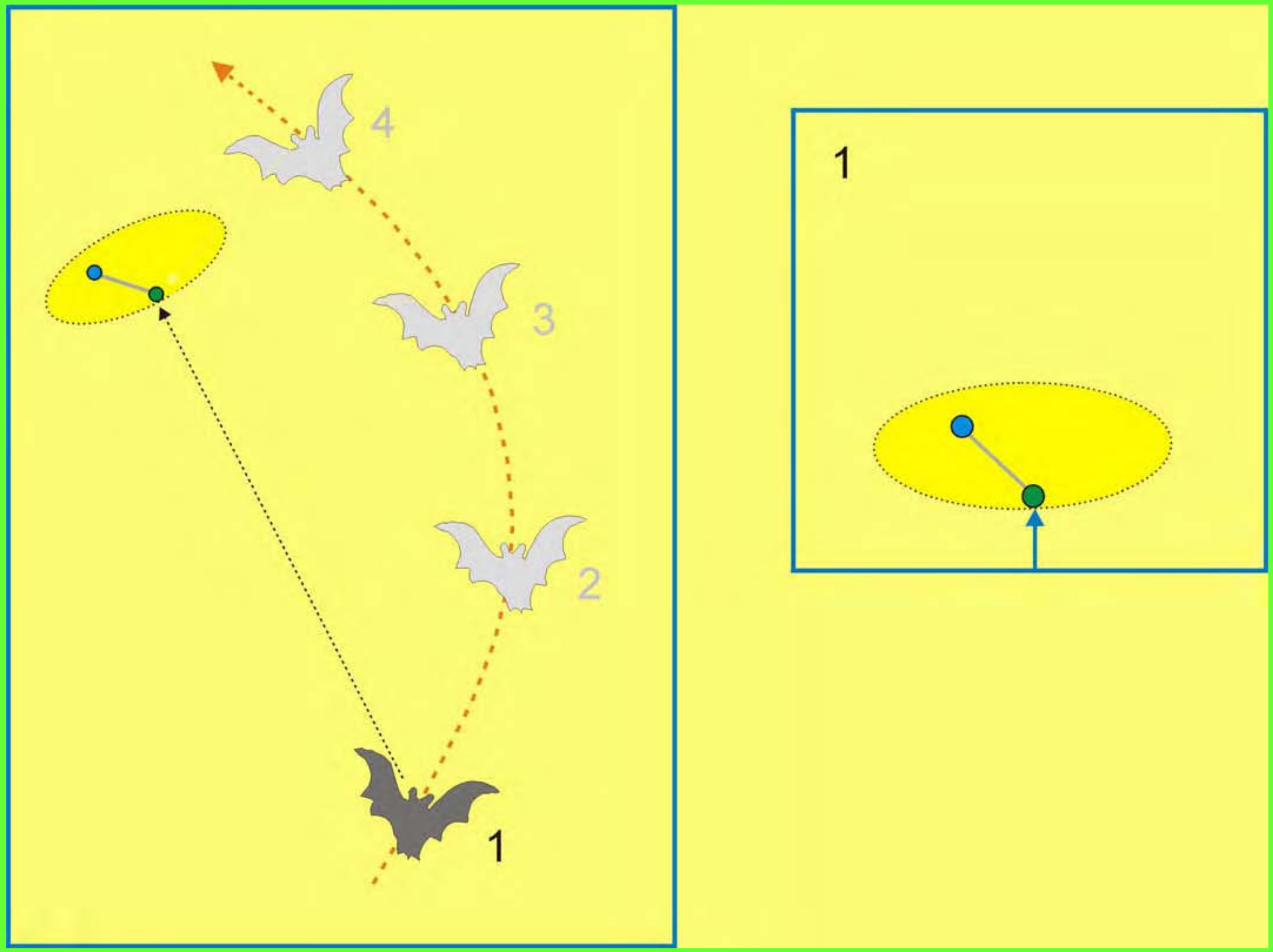
Defining An Effective Research Agenda:

Biological Systems

Les Atlas (University of Washington, visiting Univ. Cambridge),
Chris Clarke (University of Bath),
Jim Simmons (Brown University),
and **Dean Waters** (Leeds University)

Objectives

- Identify gaps in our understanding of the science and technology of bioacoustics
  - Compare and contrast bioacoustics systems and engineered systems.
  - Seek consensus on a research agenda designed to close these gaps.


4
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1
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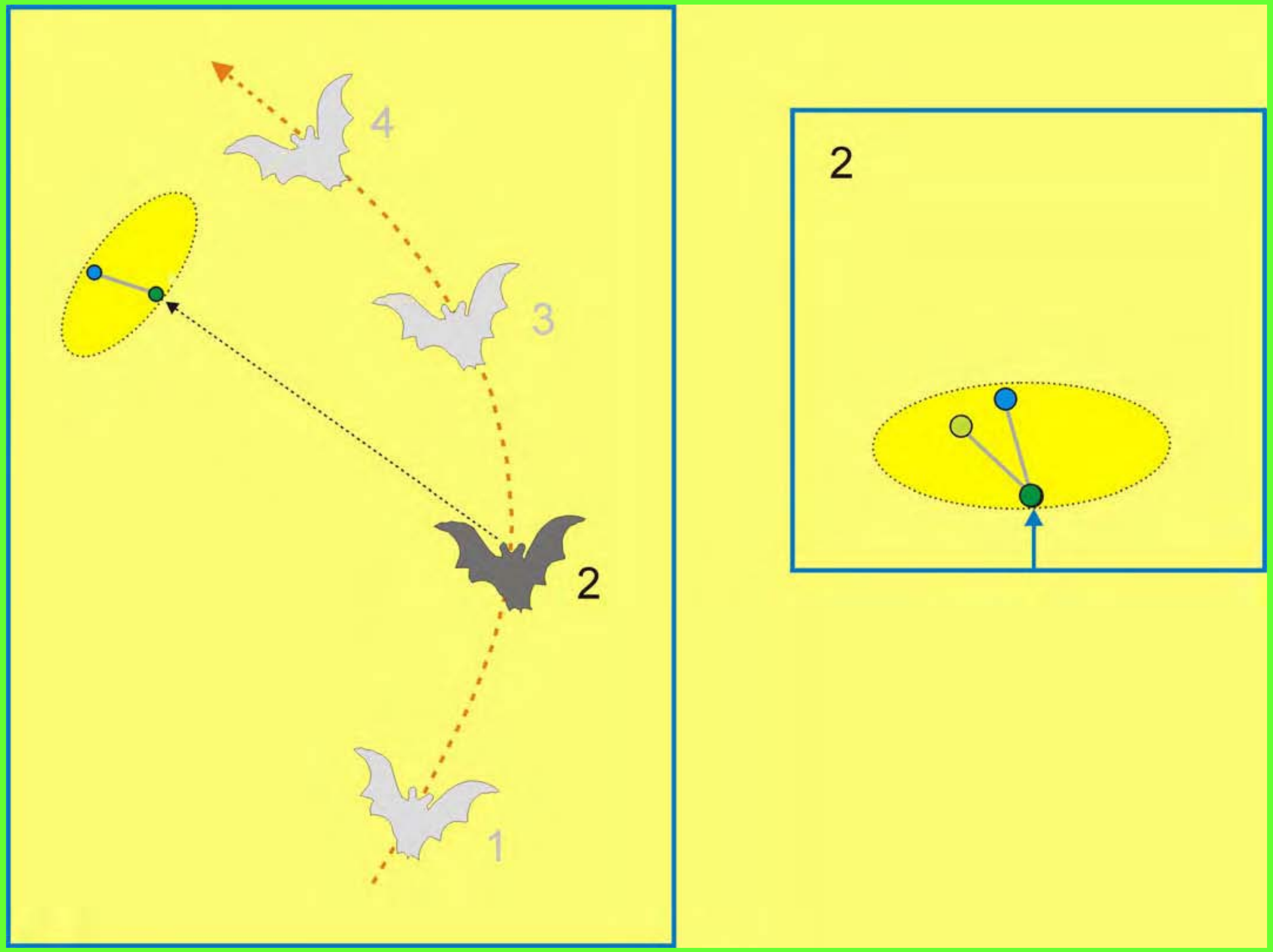
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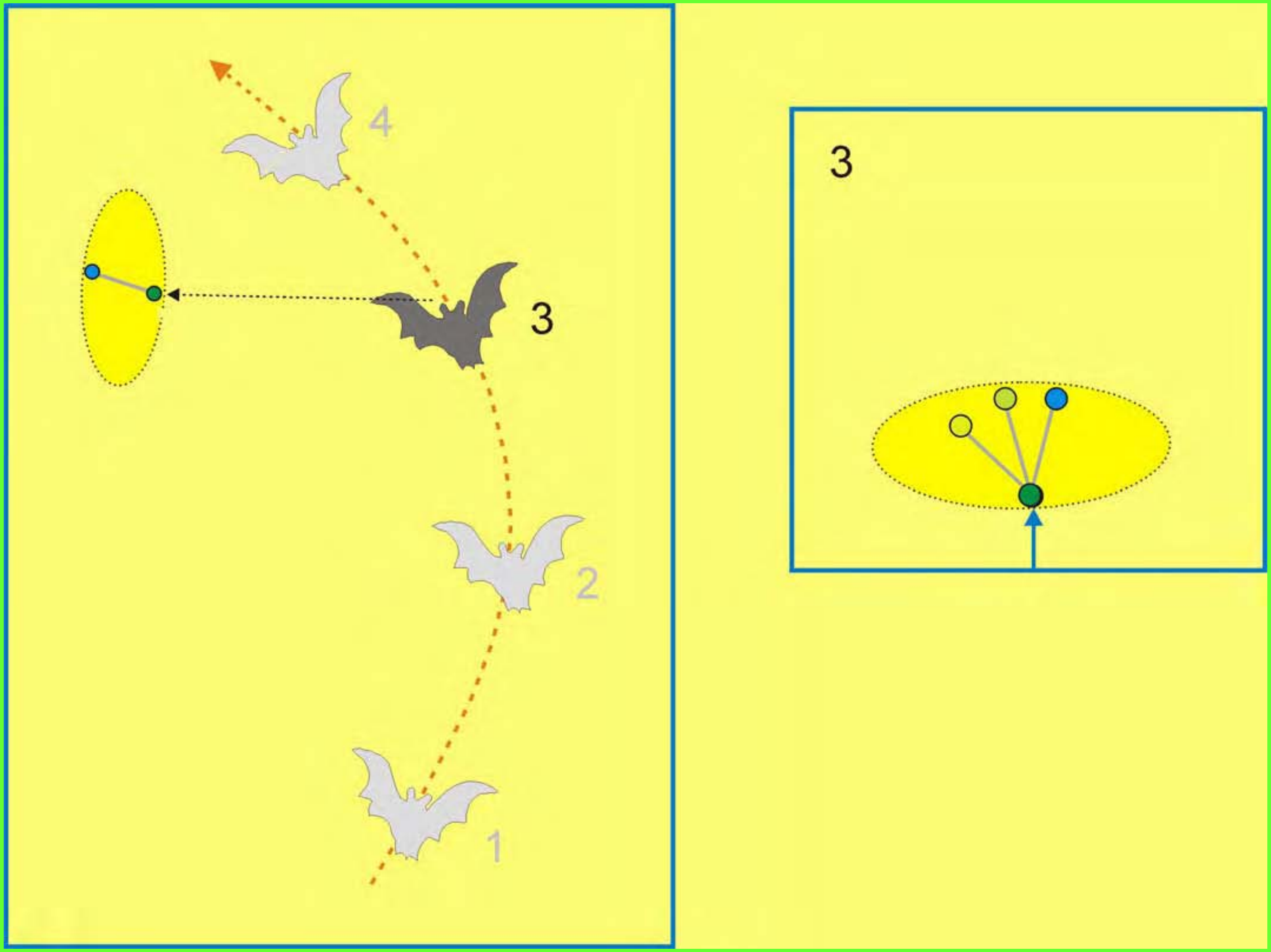
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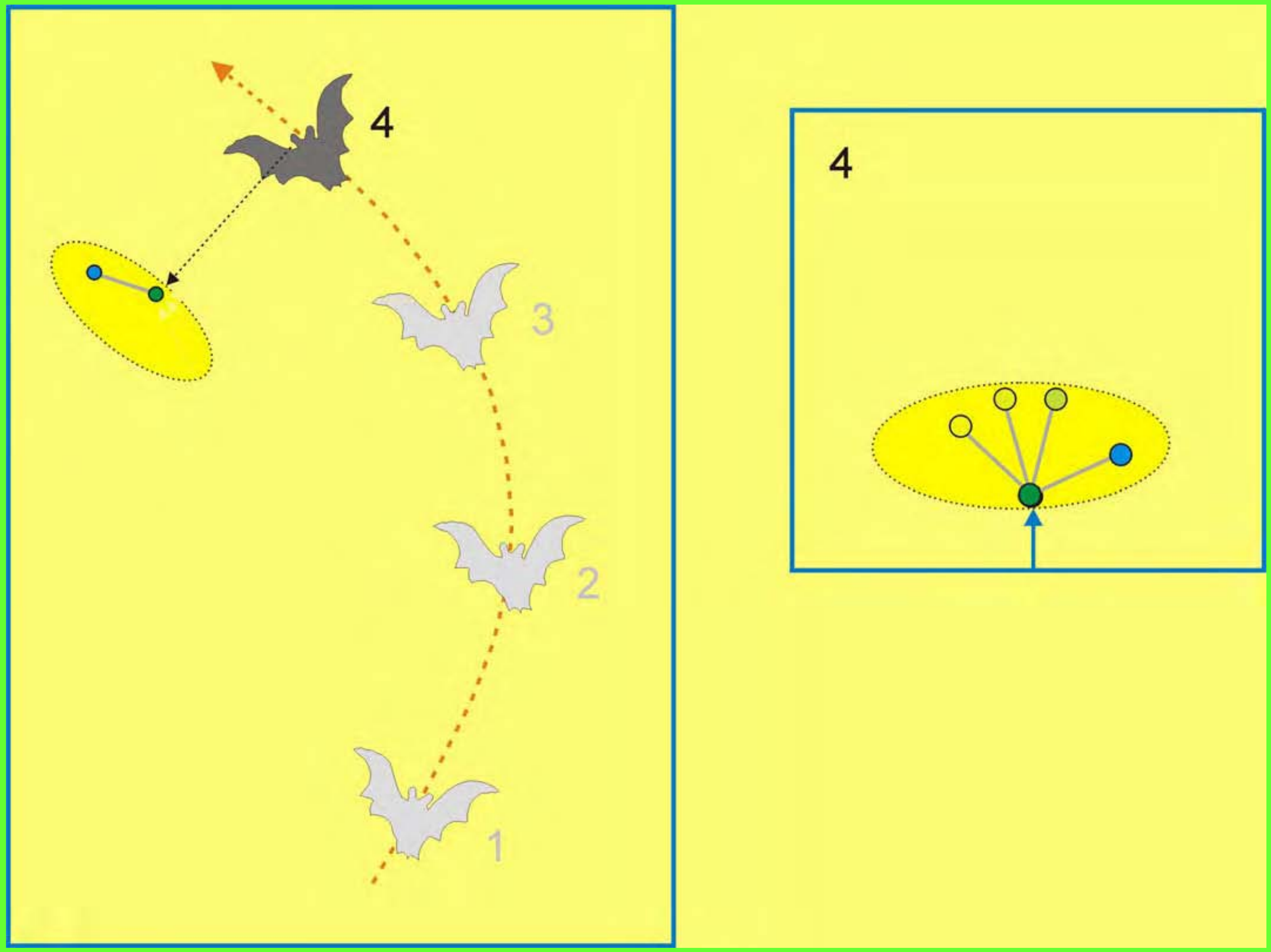
4
3
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1
4

Contrasts Between Biological and Engineered Systems A:

Target classification in sonar scenes

Biological System

- effective target selection across different environmental complexities
- reasonable sector-scan size
- efficient sequencing of tasks (*e.g.*, detection, localization, stabilization, classification)
- seamless coupling of image display to guidance and decision-making

Engineered System

- effectiveness of target selection dependent on surroundings
- sector is narrow so scan time is long and image assembly is slow, or sector is broad but images are too cumbersome
- task sequencing subordinate to DSP requirements
- poor integration of display to guidance and decision-making

What's Needed in the Research Agenda A?

- Identify aspects of biosonar performance to be achieved in man-made systems (e.g., finding targets by class)
- attack the problem of “display” as integral to guidance and classification
- leverage DoD support onto traditional funding of biological research
- develop strategy to bring large industrial/commercial resources to bear on the problem instead of funding them

Example B:

The ‘navbelt’ from the University of Michigan.

Eight transmitter/receiver pairs, processor unit of c. 5 kg.

http://www.engin.umich.edu/research/mrl/

Craseonycteris thonglongyai, the smallest bat in the world at 2g and a very proficient echolocator. One transmitter and two receivers, processor unit c. 0.1 g

Contrasts Between Biological and Engineered Systems B: Spatial map generation

Biological System

- Echolocating bats generate fast detailed spatial maps from repeated ‘probes’.
- Good ability to deal with multiple targets at multiple locations.
- Access to the map is hard-wired into the bat.

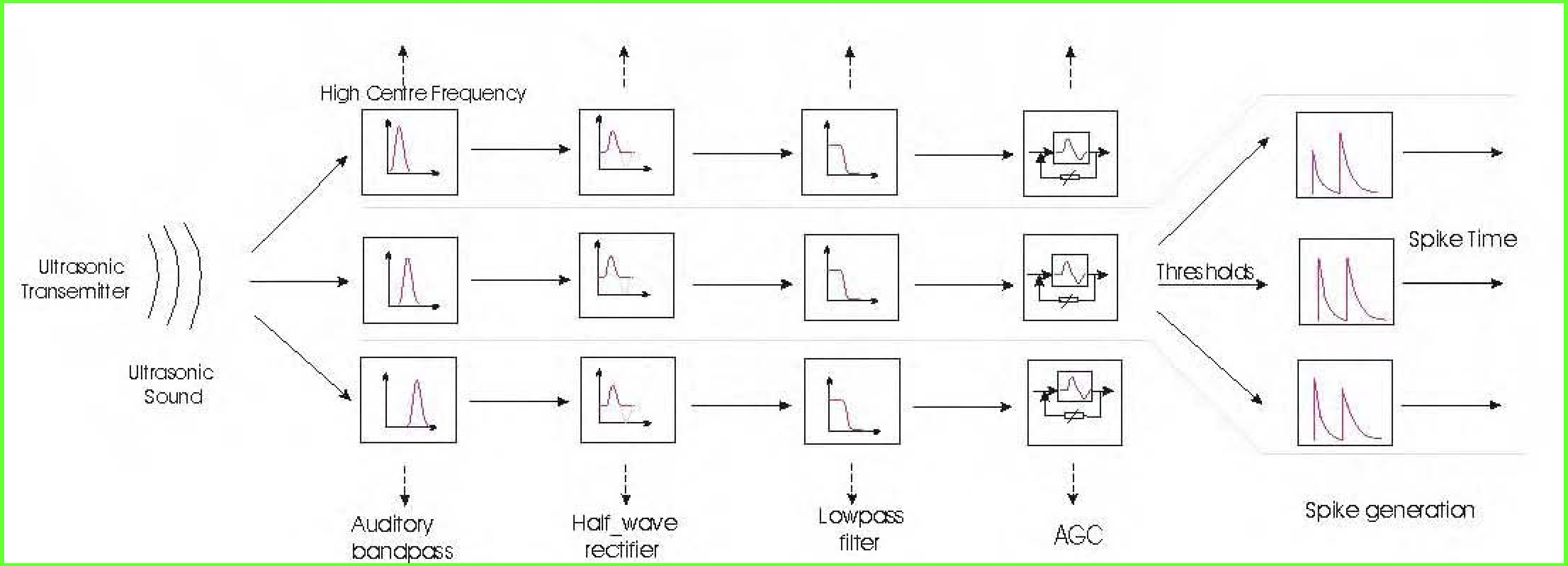
Engineered System

- Slow generation of map using data fusion.
- Limited ability to deal with multiple objects at multiple locations in space.
- Access to the map needs to be converted for interpretation.

What's Needed in the Research Agenda B?

- Better understanding of how repeated sonar images of environments are compiled into spatial maps.
  - How are multiple targets localised?
  - Redundancy of information
  - Acoustic flow (interpolation) between images

Example C:



- 100’s of channels and 10’s of thresholds
- Multi-million gate FPGA design

Contrasts Between Biological and Engineered Systems C: Ultrasonics for Navigation

Biological System

Bat Ultrasonics

- Bats navigate very effectively using wideband ultrasound
- Only one transmitter (mouth) and two receivers (ears) are needed

Engineered System

Ultrasonic Sensors

- Narrow band or single frequency systems with simple pulses
- Large sensor arrays required for accurate ultrasonic imaging

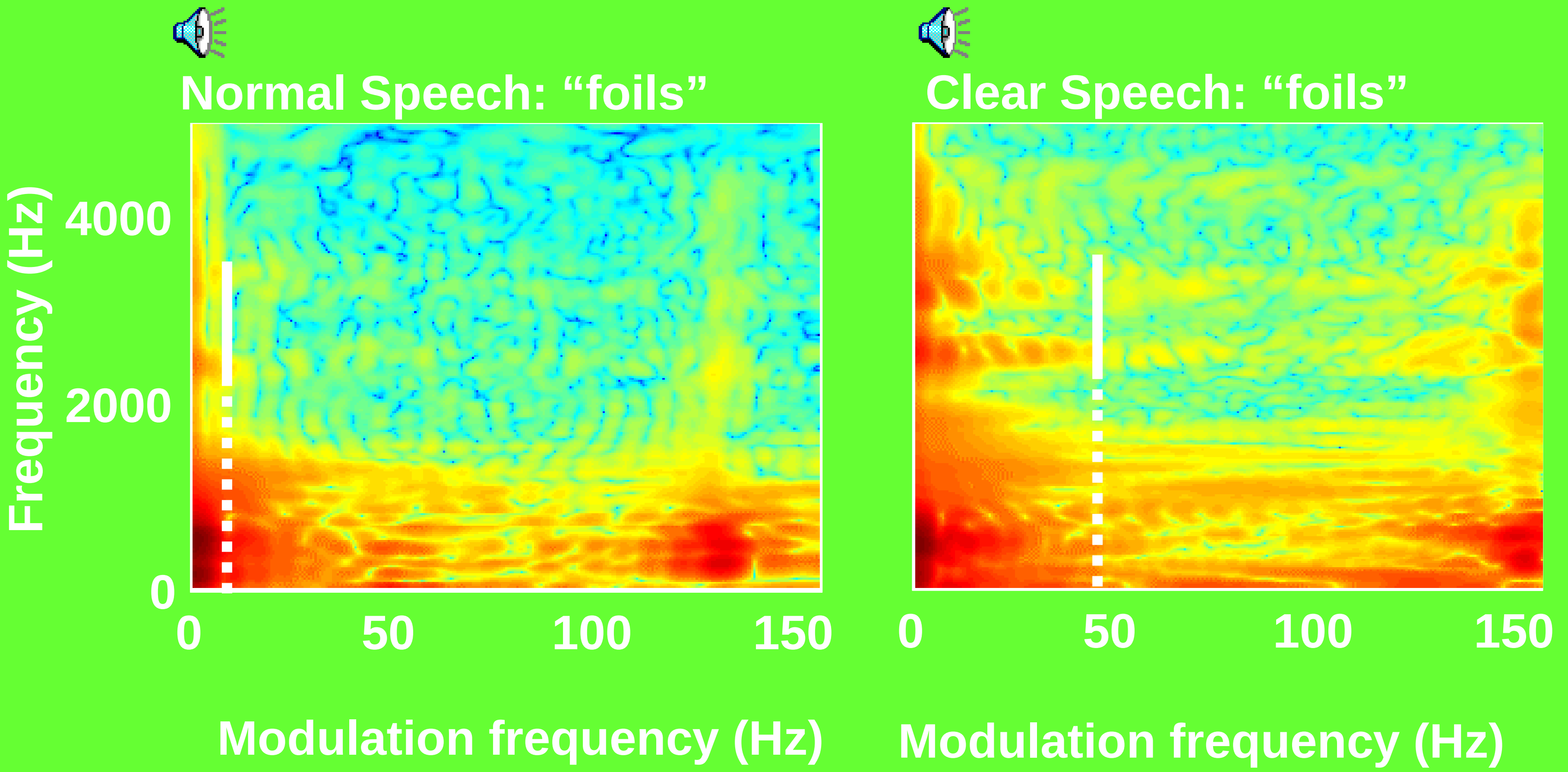
What's Needed in the Research Agenda C?

- A better understanding of the hardware complexity required for a biomimetic bat
  - Number of processing frequency bands needed
  - Number of amplitude threshold levels required
  - Adaptivity requirements

Research Needs D

- Integration of useful new signal processing tools into the biologist's toolkit for modeling and data analysis.
  - Scale Transforms
  - Modulation Spectra…

Example D: Clear Speech Analysis



Contrasts Between Biological and Engineered Systems D: Robust Human Speech Perception

Biological System

Human Auditory Perception

- Error rates for large vocabulary:
  - 0-10%*
- Solves "cocktail party" problem, namely 2-5 simultaneous speakers.

Engineered System

Automatic Speech Recognition

- One speaker only:
  - An order of magnitude* worse performance.
- Non-functional for 2 or more simultaneous speakers.

* Livescu and Glass, http://www.csail.mit.edu/research?/abstracts/abstracts03/interfaces-applications/32livescu.pdf

What's Needed in the Research Agenda D?

- Better understanding of mammalian mechanisms for sound *streaming*
  - Models of supra-cochlear processing.
  - Understanding of source and receiver as an optimal (or almost optimal) communications system.
  - Willingness of signal processing researchers and biologists to go beyond standard frequency- transform based mathematics.

Summary: Biological Systems Research Agenda

A. What is the underlying compressed representation of the acoustic space.
B. How are spatial maps generated from multiple sonar images?
C. What level of cochlear modeling is needed for complex navigation problems?
D. What makes mammalian audition robust to multiple simultaneous sound sources?

Appendix 3l

Ivars Kirsteins

Processing Bioacoustics Signals

Ivars P. Kirsteins
Naval Undersea Warfare Center
1176 Howell St.
Newport, RI 02879 USA

Engineered Systems vs. Biological Systems

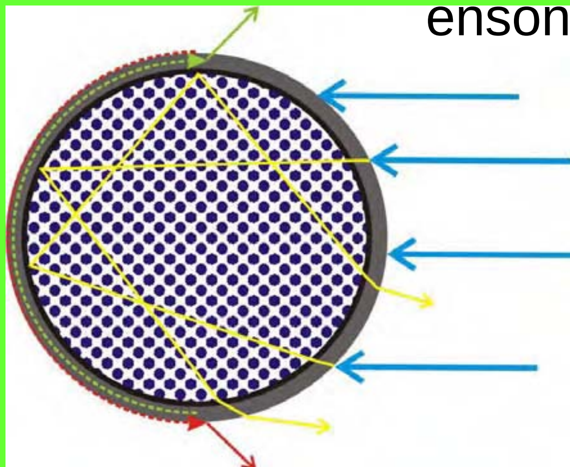
Engineered Sonar Systems:

- ❖ detailed descriptions (models) of signal and noise and scenarios
- ❖ IF … THEN … ELSE approach – try to account for every possible possible situation and permutation
  - ➢ *poor performance in unexpected scenarios*
  - ➢ *design methodology overwhelmed by combinatorics*

Biological Sonar Systems:

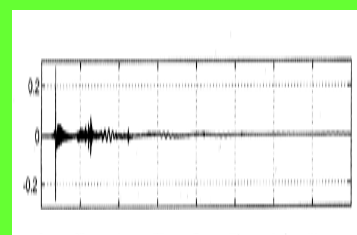
- ❖ biological systems are highly flexible
- ❖ almost unlimited capability for in-situ adaptivity or learning
  - ➢ *adapt easily to new signals and situations*

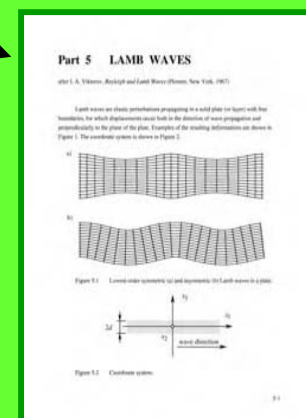
Example: Mine Classification

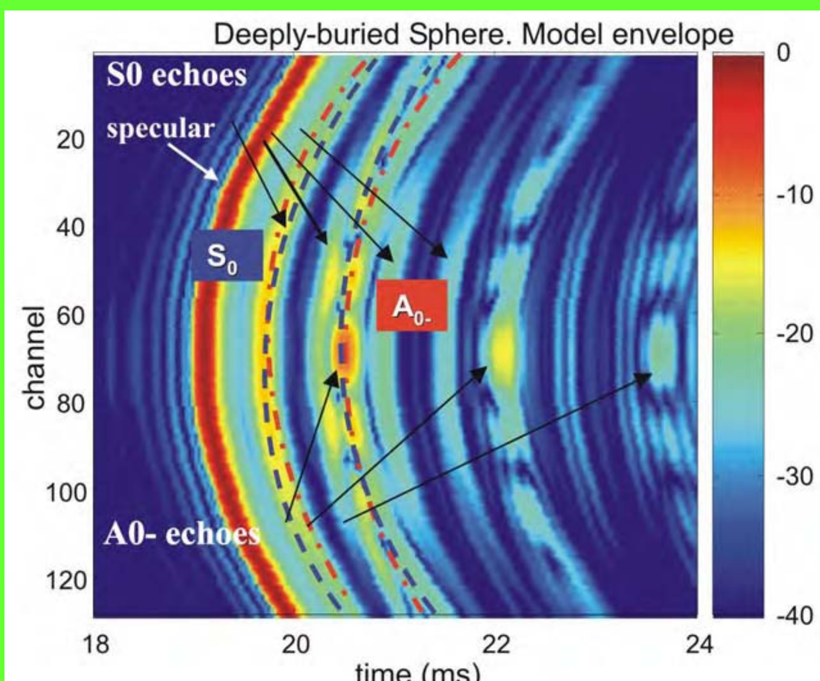


ensonified mine

- specular echoes
- internal structural scattering
- Lamb-type elastic waves – A_0 and S_0 waves

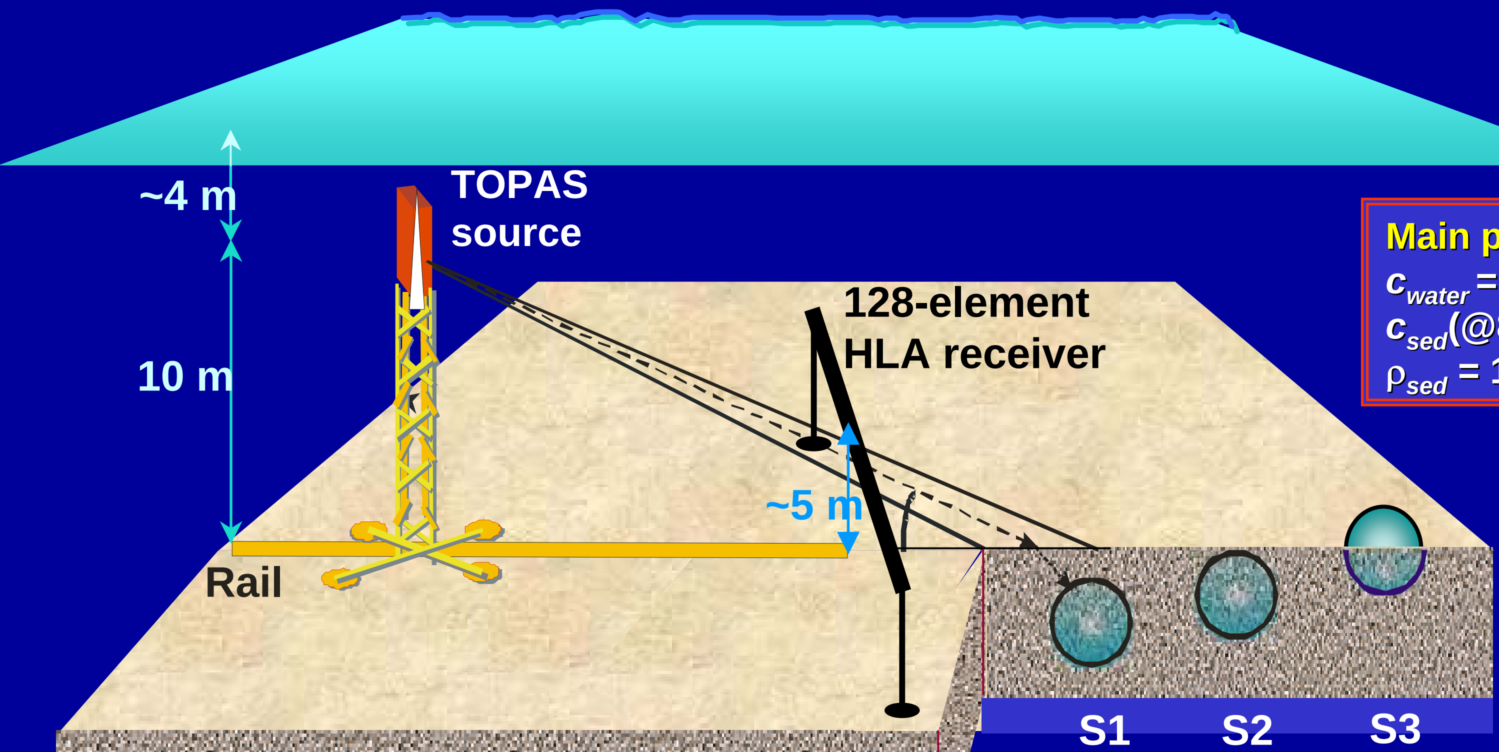


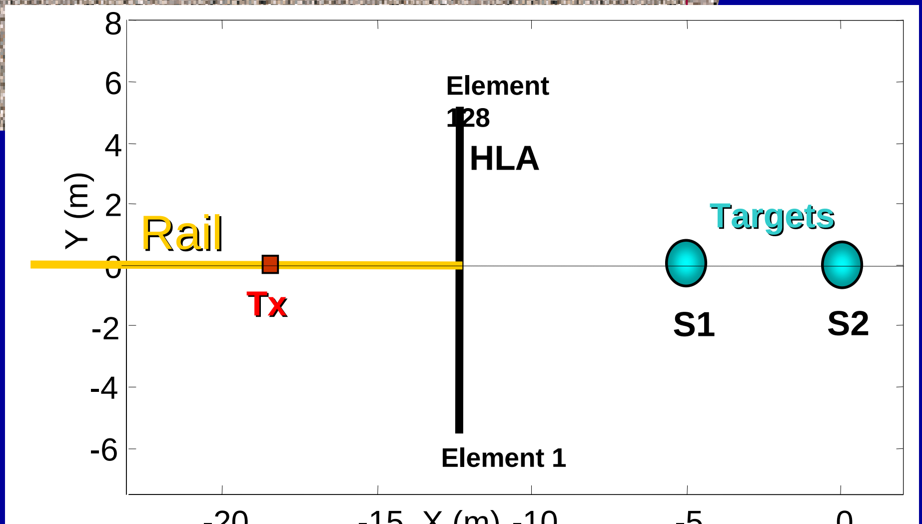




❖ Internal structural scattering and A_0 and S_0 waves are a function of the mine shape and construction and therefore potential classification features

SACLANTCEN trial geometry *(GOATS'98)*





Main physical parameters:

c_{water} = 1520 m/s

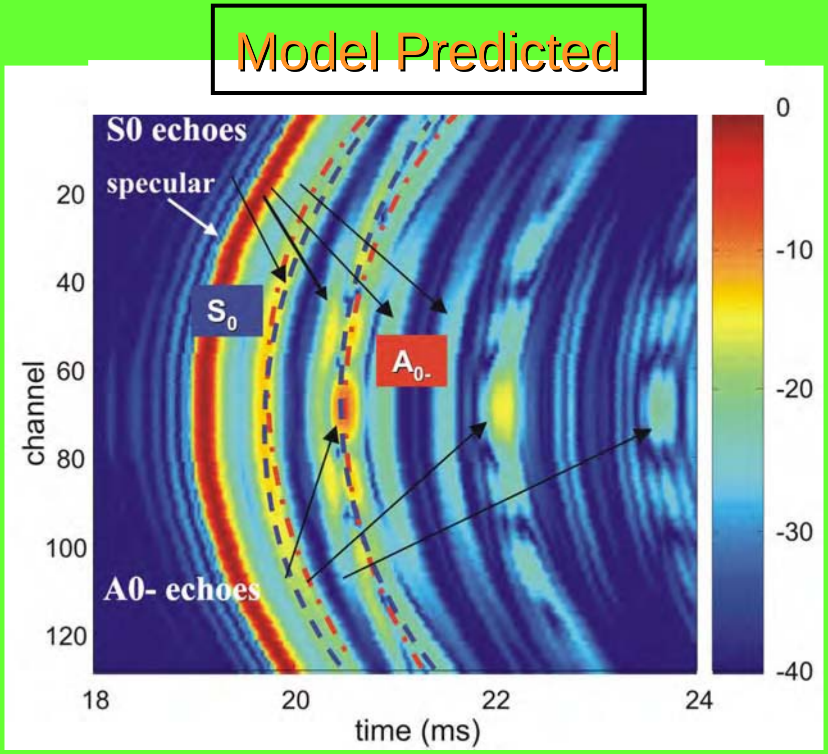
c_{sed}(@8kHz) ≅ 1640 m/s

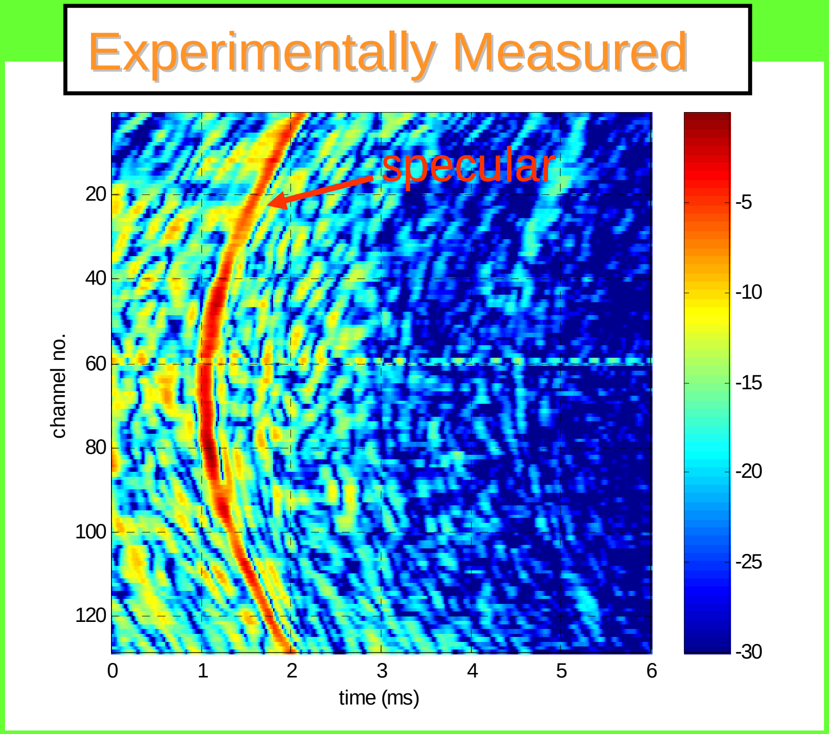
ρ_{sed} = 1.9 g/cm^3

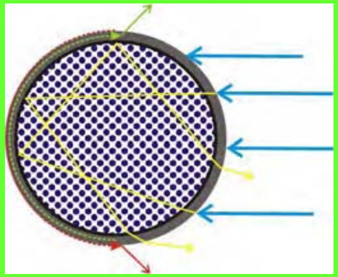
Target:

- **Air-filled, thin-walled sphere**
- **53 cm radius, 3 cm thick wall, steel**

At-Sea Experiment Data







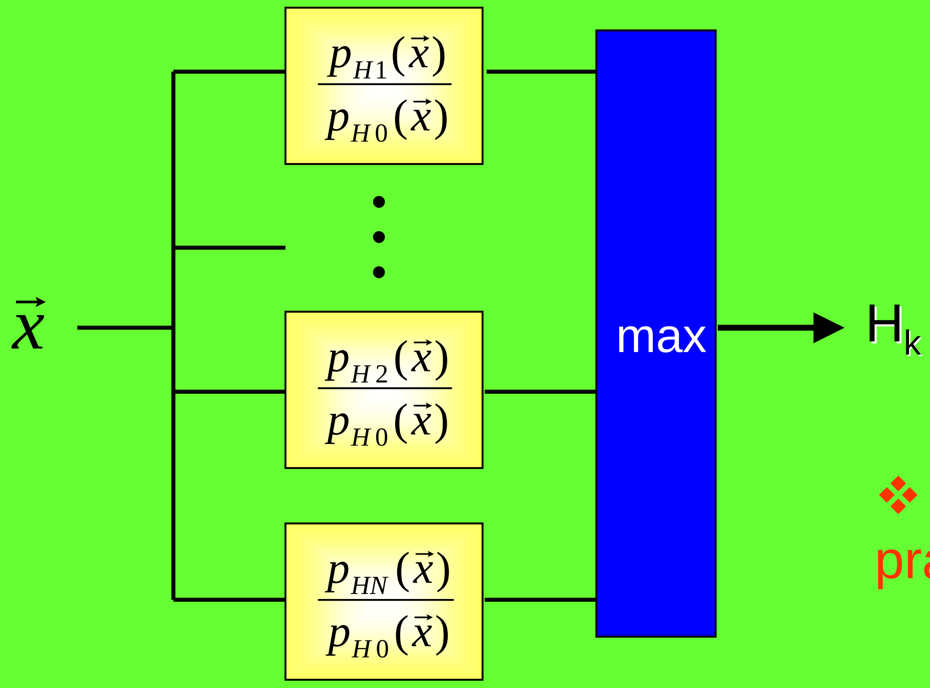
- At-sea data is noisy
- Many different environments and geometries
- Many types of mines
- Not clear how to parameterize mine echo and noise fields

Idealized Statistical or Bayesian Engineering Approach

Describe the world statistically, taking into account every possible scenario or permutation

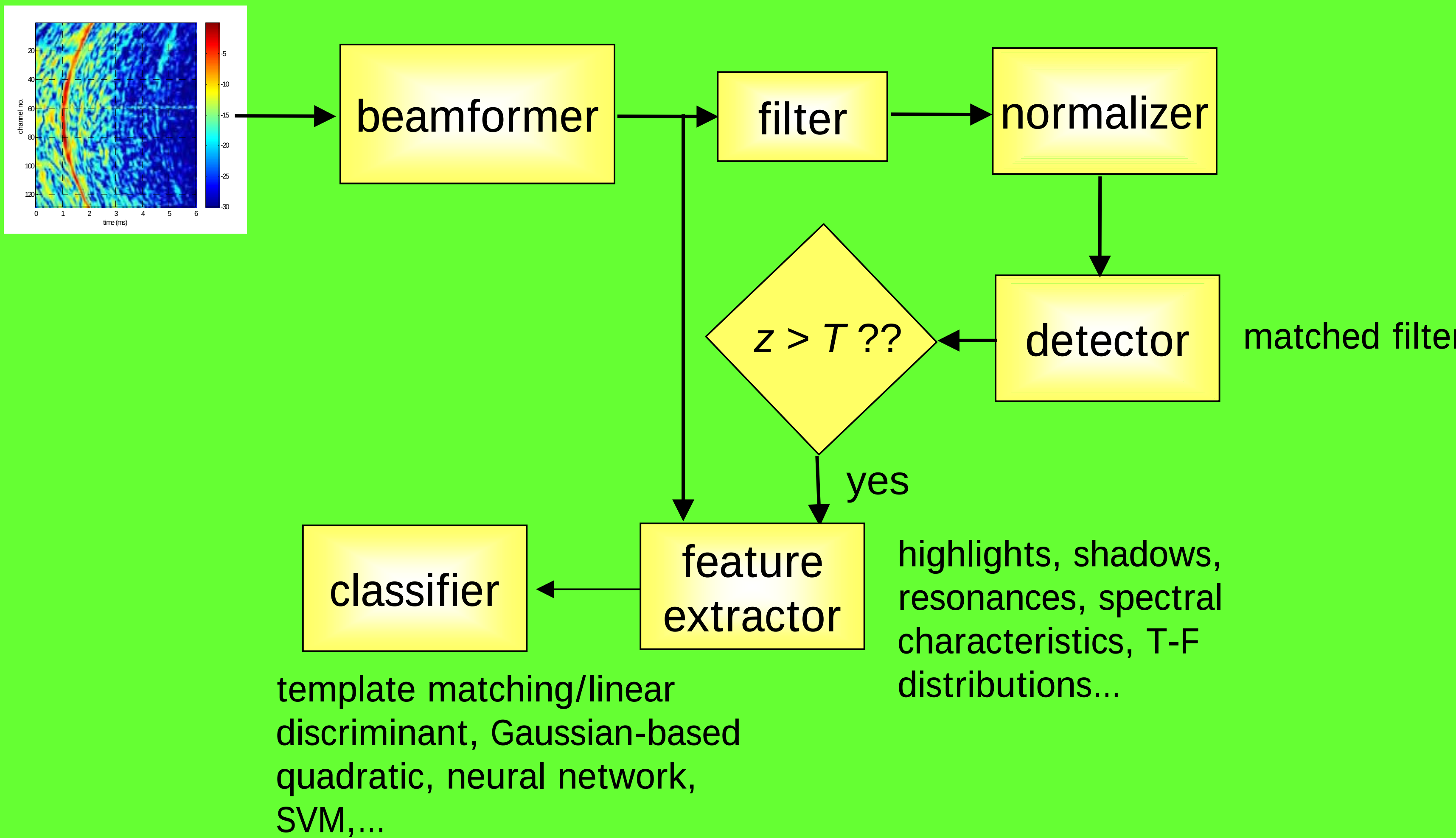
- object type, signal and noise fields…

Example: bank of likelihood-ratio tests



❖ in most cases not feasible or practical!!

Practical Engineering Implementation



- ➢ Accounting for all possible permutations/scenarios is difficult
- ➢ Hard to determine and model the features essential for classification and suppressing noise

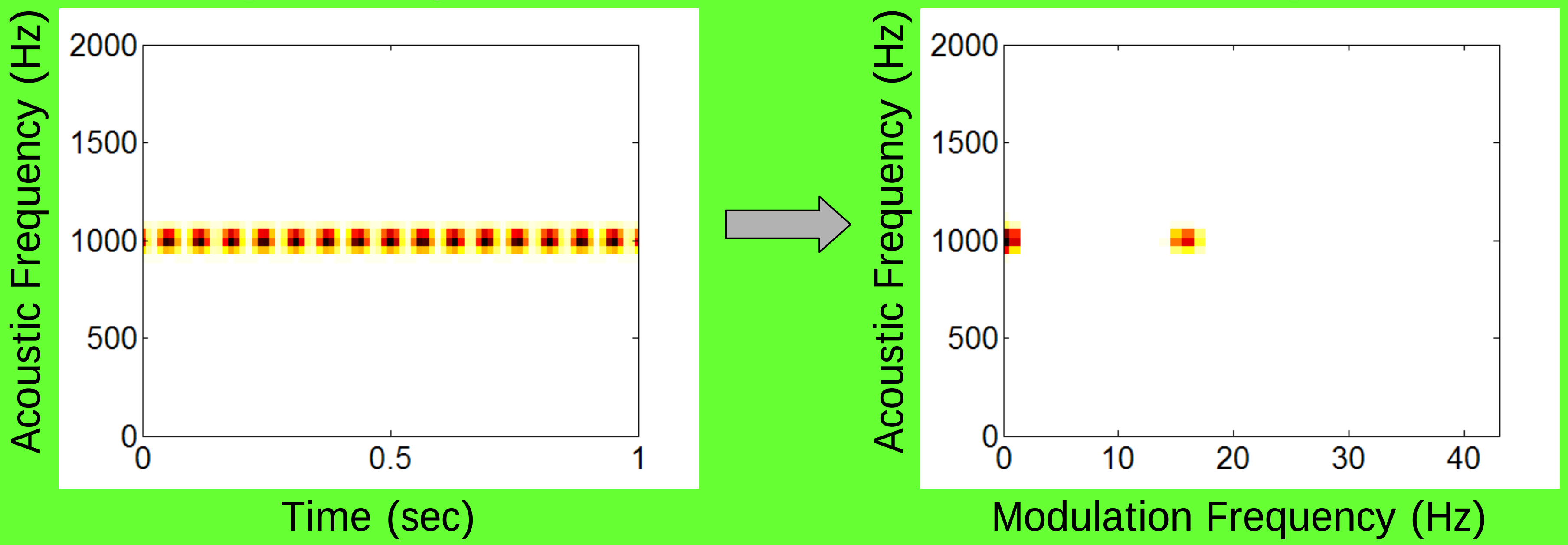
Observations

- Humans and animals do remarkably well in recognizing sounds in in complex and low signal-to-noise ratio environments and are highly adaptive to new situations
    - *much research has gone into automatic speech recognition and auditory scene analysis*
    - *some progress, but still much difficulty in handling arbitrary sounds/speakers and noisy environments, e.g. cocktail party effect*
    - *sonar problem similar – active and passive*

- Traditional engineering approaches cannot seem to able to solve the problem

Two Representations of Sound – Les Atlas

Spectrogram **Modulation Spectrum**



Modulation Spectra – Les Atlas

- Remaining research questions and opportunities:
  - Precise mathematics and physics:
    For example, what's the precise definition of modulation frequency?
  - How to simultaneously track multiple sources of coherence?
  - Applications outside speech and human auditory perception.

Biologically Motivated AM-FM Signal Representation

Investigated application of product AM-FM signal representation scheme of Kumaresan (1997) for segregation of tonals by common modulation characteristics (Bregman, Auditory Scene Analysis) to passive sonar data

- *Kumaresan speculated that the ear may be doing some form of non-linear processing*

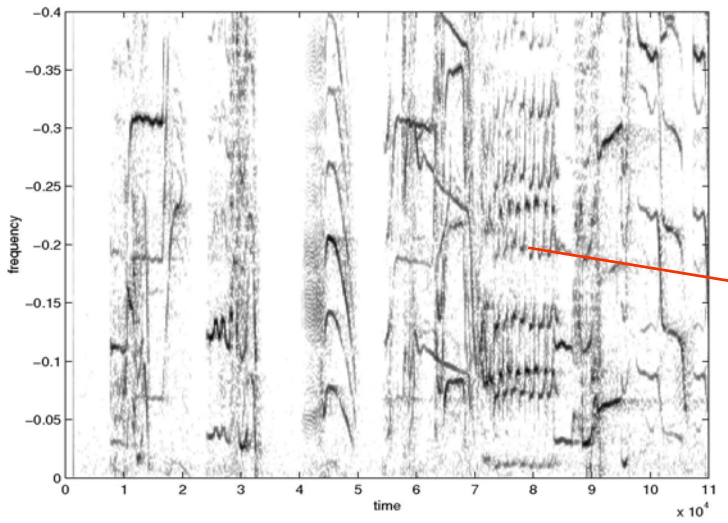


Figure 1: Spectrogram of killer whale vocalizations.

$$s(t) = \sum_{k=1}^{K} a_k(t) \cos(\phi_k(t))$$

$$s_k(t) = \underbrace{\prod_{k=1}^{P}(1 - p_k e^{i\omega t}) \prod_{j=1}^{Q}(1 - \frac{1}{q_j^*} e^{i\omega t})}_{a_{MinP}(t)} \underbrace{\frac{\prod_{j=1}^{Q}(1 - q_j e^{i\omega t})}{\prod_{j=1}^{Q}(1 - \frac{1}{q_j^*} e^{i\omega t})}}_{e^{i\Theta_{AllP}(t)}}$$

"AM" "FM"

Biologically Motivated AM-FM Signal Representation

Application to whale vocalization:

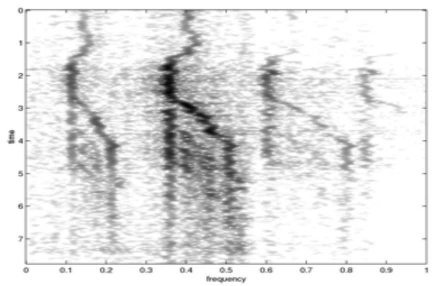


Figure 2: Spectrogram of humpback whale vocalization.

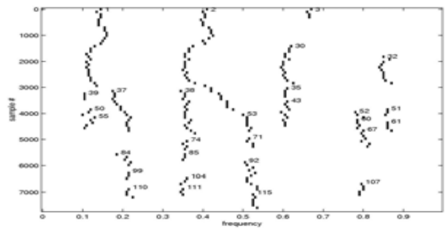


Figure 3: Detected coarse narrowband tracks.

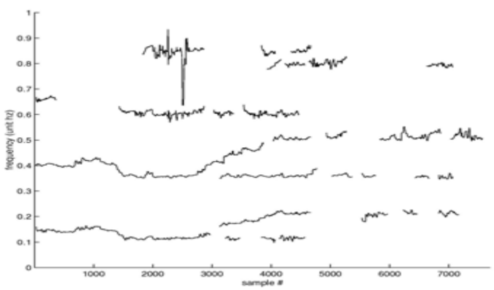


Figure 4: Estimated IF components after smoothing by a order 33 median filter.

Challenge: Underwater signals are weak and characterized by rapid fading, and embedded in strong non-stationary interference

- Implementation and automation proved difficult and non-trivial

Knowledge Gaps and Research Agenda – A. Trucco & W. Zimmer

Gaps:

- How is phase information exploited in bioacoustic systems
- Bioacoustic signal processing concepts to achieve high directivity
- Mechanisms ruling adaptation of pulses emitted over time
- Why do some bioacoustic systems employ multi-frequency transmission? What are the non-linear processing techniques used for their exploitation?

Agenda:

- ❑ Overview of bio-mimicking systems designed till now and consensus report on advantages/disadvantages over traditional systems
- ❑ Attempt to introduce bioacoustic concepts into existing sonar systems to improve their performance – medium term research
- ❑ An attempt to design a high performance visionary system, fully integrating known bioacoustic concepts (e.g. synthetic dolphin) – long term research

Knowledge Gaps and Research Agenda – I. Kirsteins

My Observation: Good progress has been made in understanding the transducer and lower level bioacoustic processing components of animals and humans. But,

❖ Signal “representations” / information used by bioacoustic systems not completely understood yet – non-parametric vs. parametric etc.

❖ Better understanding of the higher level processes of cognition/recognition are needed – how is the lower level information assimilated and exploited by the brain, how is the neural processing for cognition done,…?

- ➢ signal attributes used
- ➢ cognition processes

- ❖ Biological information processing systems are amazingly flexible and adaptive. Can a purely reductionist/engineering approach ever completely unravel the architecture/algorithms of the higher-level processes for auditory cognition by the brain and duplicate the functionality of biological systems??

> ➢ Alternative approaches? Presently there is much research going on (e.g. Santa Fe Institute) in understand large-scale non-linear systems, self-organization, evolutionary computing, etc. Should we be looking at this?

Appendix 3m

Tengiz Zorikov

Bio-mimetic sonar: results achieved and the road to improvement

The data on echo-image formation in bottlenose dolphins, revealed in our experiments and used in the model

1. Signal components highlighted within a time interval ~200 μs (the Critical Interval of Time – CIT) produce a merged auditory image in a bottlenose dolphin's perception.
2. By analysis of echo within that time window, bottlenose dolphin utilizes the string of three independent, hierarchically interrelated discriminative features being determined by the different scale of spectral density oscillations of an echo and by its energy, namely:
   – the first in hierarchy, senior Feature "MaPS" (Macrostructure of a Power Spectrum) being defined by large-scale variations of echo's Power Spectrum Density (PSD), exceeding ~10 kHz frequency bandwidth;
   – the second in hierarchy, middle in triad Feature "MiPS" (Microstructure of a Power Spectrum) being defined by small-scale oscillations of echo's PSD with the periods in the interval ~5-10 kHz;
   – the last in hierarchy, minor Feature "Energy" being defined by the energy of an echo within the CIT.
3. Bottlenose dolphin is capable to estimate the features' average values over a series of echoes.
4. Bottlenose dolphin, distinguishing echoes, compares successively their features' values from senior to minor, terminating the process at a feature that contains detectable differences (the distinctive feature).
5. Subsequent identification of the reference signal obeys the following decision rule: If bottlenose dolphin utilizes a particular feature as the distinctive one, then in order to preserve the image of the reference signal, it is necessary and sufficient to preserve the same values of the distinctive feature and all higher ones in order of hierarchy.

Estimation of the features' MaPS, MiPS and Energy values in the model

Feature MaPS (senior) is represented by 16-dimensional vector, the components of which are determined by the formula (1):

(1)

$$\underset{j=\overline{1,16}}{mac_j} = \frac{\int_{f_{j-1}}^{f_j} \left|F\left\{x(t)\right\}\right|^2 df}{\int_{f_0}^{f_{16}} \left|F\left\{x(t)\right\}\right|^2 df}$$

Feature MiPS (middle) is represented by 19-dimensional vector, the components of which are determined by the formula (2):

(2)

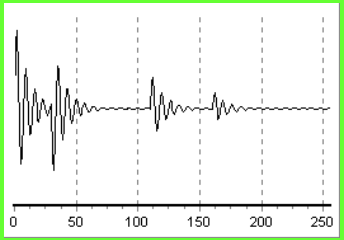
$$\underset{j=\overline{1,19}}{mic_j} = \frac{1}{\left[1+0.05\left(j-1\right)\right]} \int_{\tau_{j-1}}^{\tau_j} \left| F^{-1}\left\{ \ln\left[\frac{\left|F\left\{x(t)\right\}\right|^2}{\int_{f_0}^{f_{16}} \left|F\left\{x(t)\right\}\right|^2 df} + 1 \right] \right\} \right|^2 d\tau$$

Feature Energy (minor) is calculated by integration of echo's PSD over the diapason of bottlenose dolphin sonar perception (30–190 kHz), the formula (3):

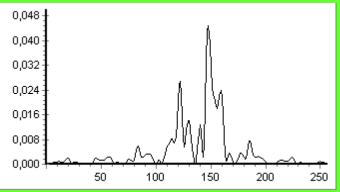
(3)

$$E = \int_{f_0}^{f_{16}} \left|F\left\{x(t)\right\}\right|^2 df$$

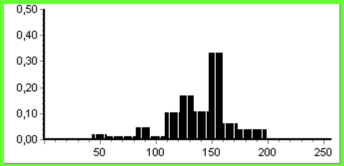
Echo *x(t)*



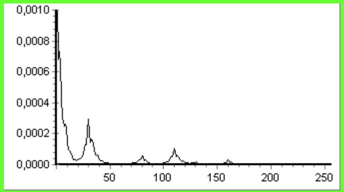
Echo's PSD



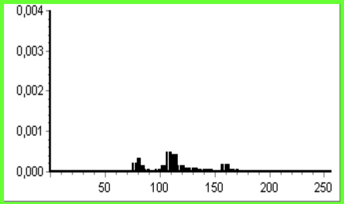
Feature MaPS



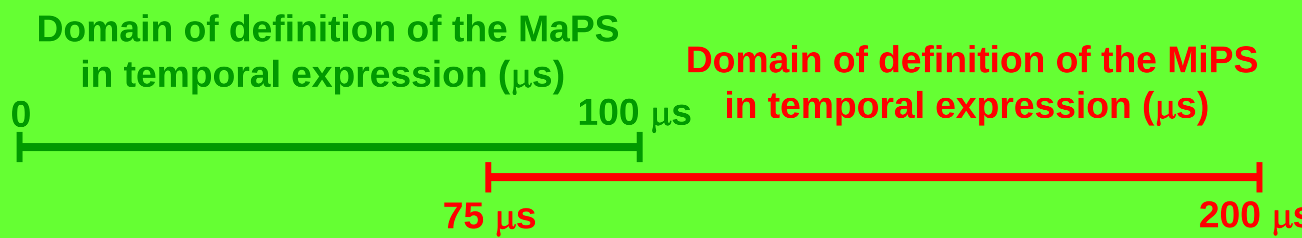
Echo's Cepstr



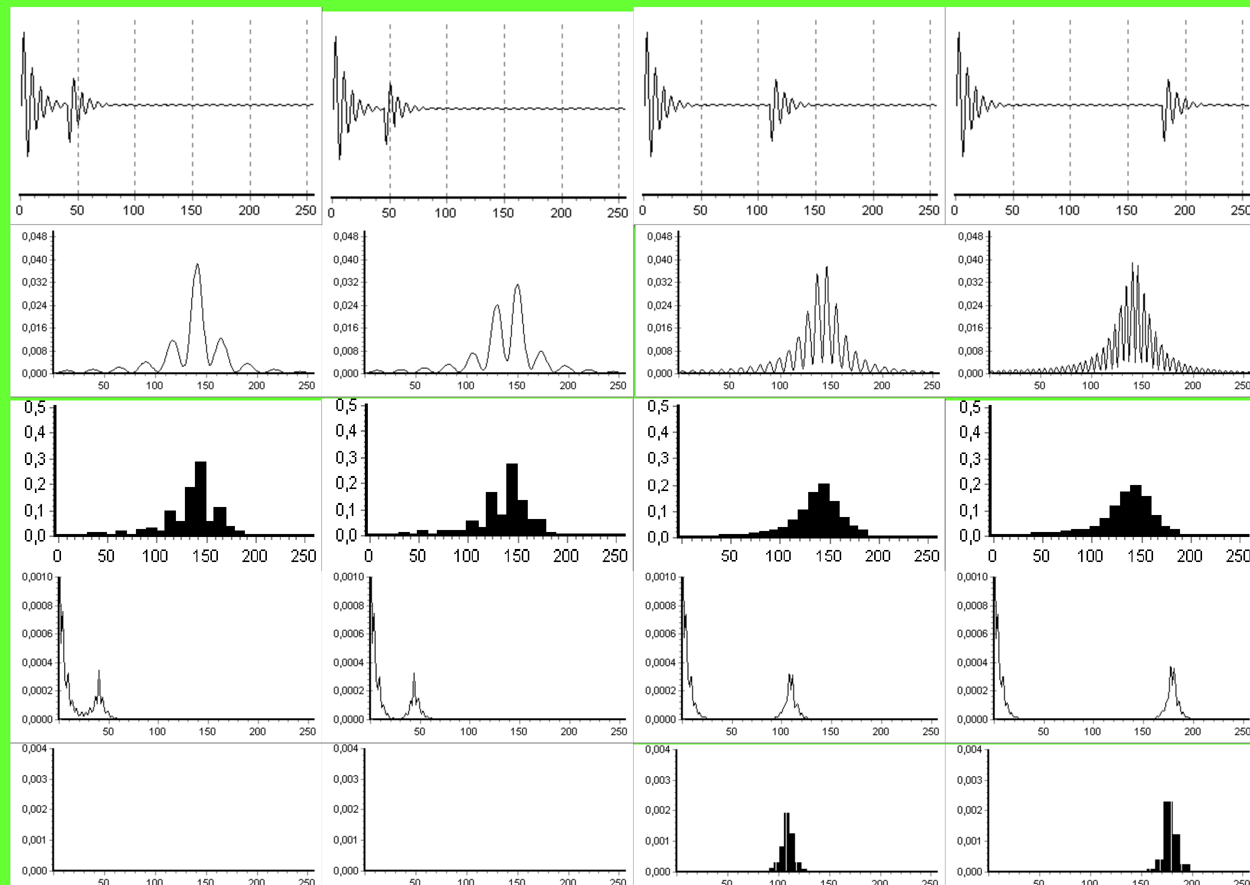
Feature MiPS



Features' MaPS and MiPS performance within the Critical Interval of Time



Interpulse interval	40 μs	45 μs	110 μs	180 μs



The process of training the model

At the first step the average values of the discriminative features (MaPS, MiPS and Energy) are calculated on a large set of echoes from a target intended to recognition -- the features' standards of that target, as well as the confidence intervals for each of these features, which in turn are calculated on the large number of subsets of echoes from the given target. These parameters, - three standard values of features and confidence intervals, appropriate to them, are kept in program database. Such simple way of accumulation of the data allows easily updating of a database by simple adding to it of new images (the sets of parameters above mentioned).

The echo-recognition process

Recognition of an unknown target is carried out by comparison of the average values of features, which are calculated on the subset of echoes from that unknown target, with the features standards stored in database. The features are compared successively, from the senior (MaPS) up to minor (Energy). The recognition process is finished successfully, when any feature of an interrogated target will get within the limits of a confidence interval of an appropriate feature standard of a concrete target from the database.

Model's performance:

We have tested the model on synthetic two-highlight echoes in a wide range of variations of their temporary and amplitude relationships. We used also stochastically distributed parameters and white noise for the maximal approaching the simulated conditions to natural ones. Such approximation is good enough to make a conclusion about expediency of realization of the further tests of model on echoes from actual targets.

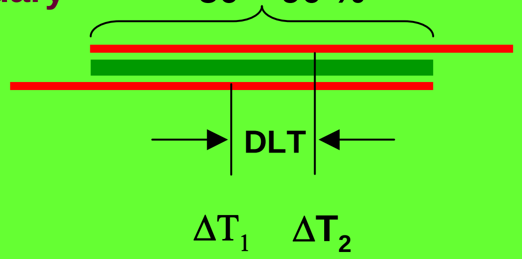
1. Discrimination of synthetic two-highlight echoes with random intervals.

ΔT -- Average value of a time delays of a secondary pulse

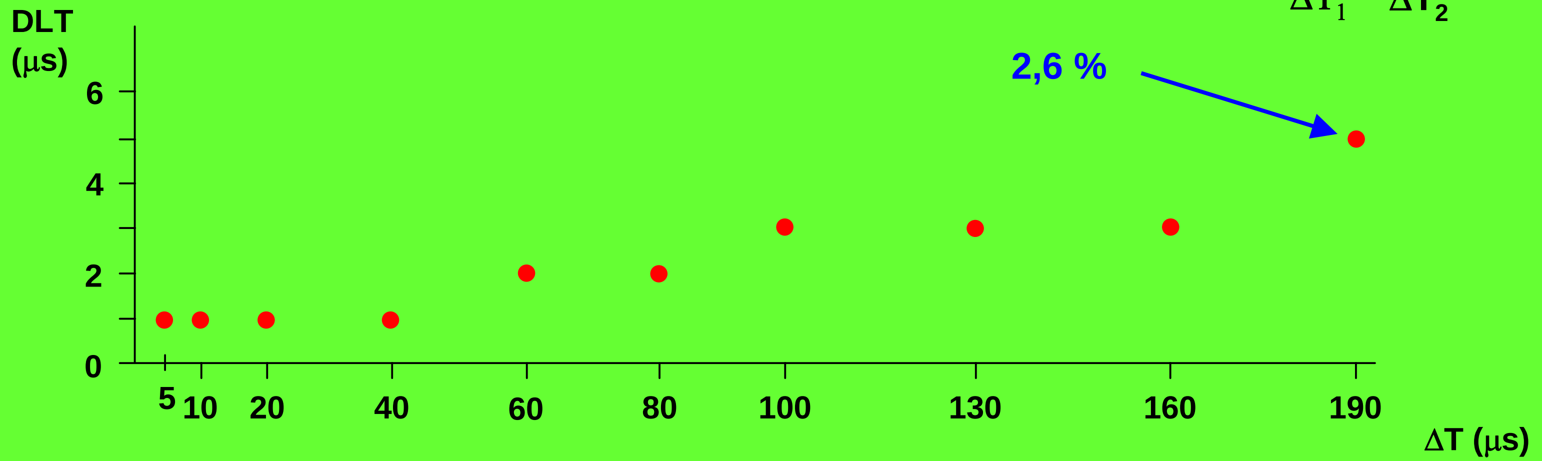
L -- Diapason of variation of a secondary pulse position (red line) L = 0,4 ΔT

Thereby the share of intersection of intervals of variation of the secondary pulses (green line) of signals discriminated by the model changes in the given conditions from 50 up to 90 %, along with ΔT increasing

50 – 90 %

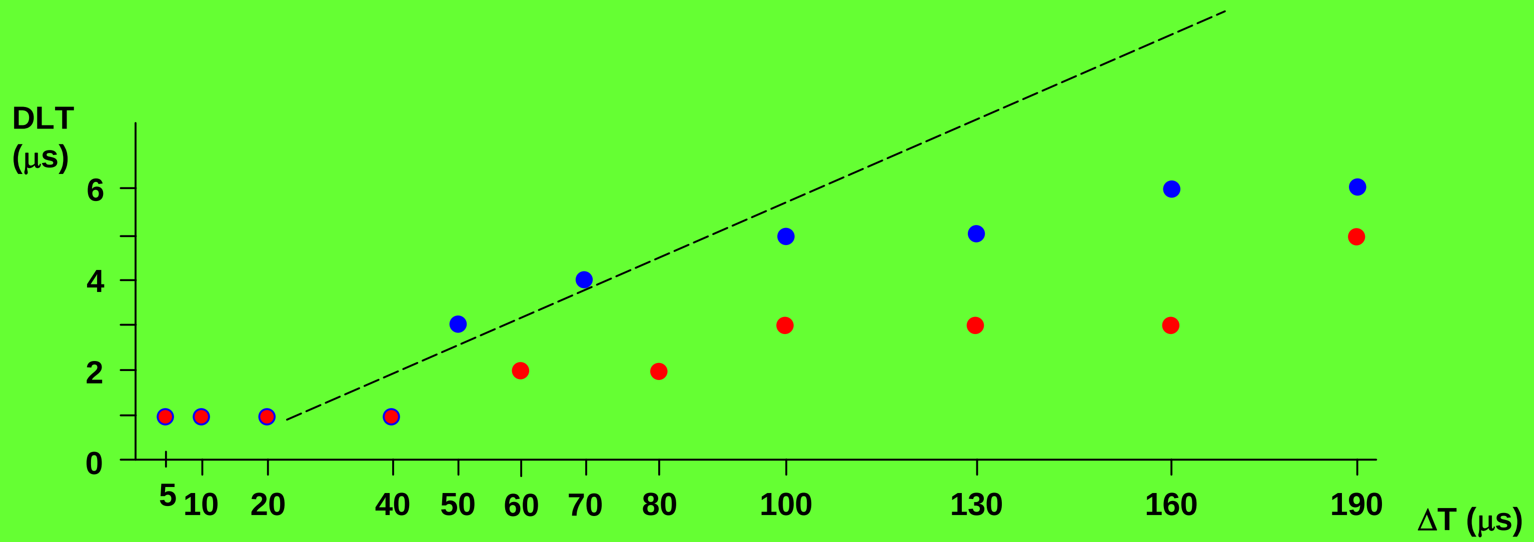


DLT -- Difference liman for time intervals $DLT = \Delta T_1 - \Delta T_2$



2. Discrimination of two-highlight echoes with random intervals in the white noise

Signals of the same type as above, on a background of 0,25 amplitude white noise (the signal energy -to -noise ratio was about 12 dB) were used in this measurement. Adding noise has caused increase of the thresholds for DT > 40 μs (blue points ●) in comparison with the previous data (red ones ●). The dashed line corresponds to the limiting capability of bottlenose dolphins to distinguish two-highlight stable-structure signals, measured in good hearing conditions (about 5%). Thus, conducted measurements demonstrate considerable advantage of the model in discrimination of time intervals. Some deterioration of the model sensitivity was revealed within an area around 50 – 100 μs. Rather presumable is that we could remove this lack in future, having increased area of intercrossing of the domain of definition of features MaPS and MiPS by displacing ones more the bottom boundary of the domain of definition of the feature MiPS. However obtained data are already better then those of dolphins in any case, taking into account stochastic character of the intervals and noise.

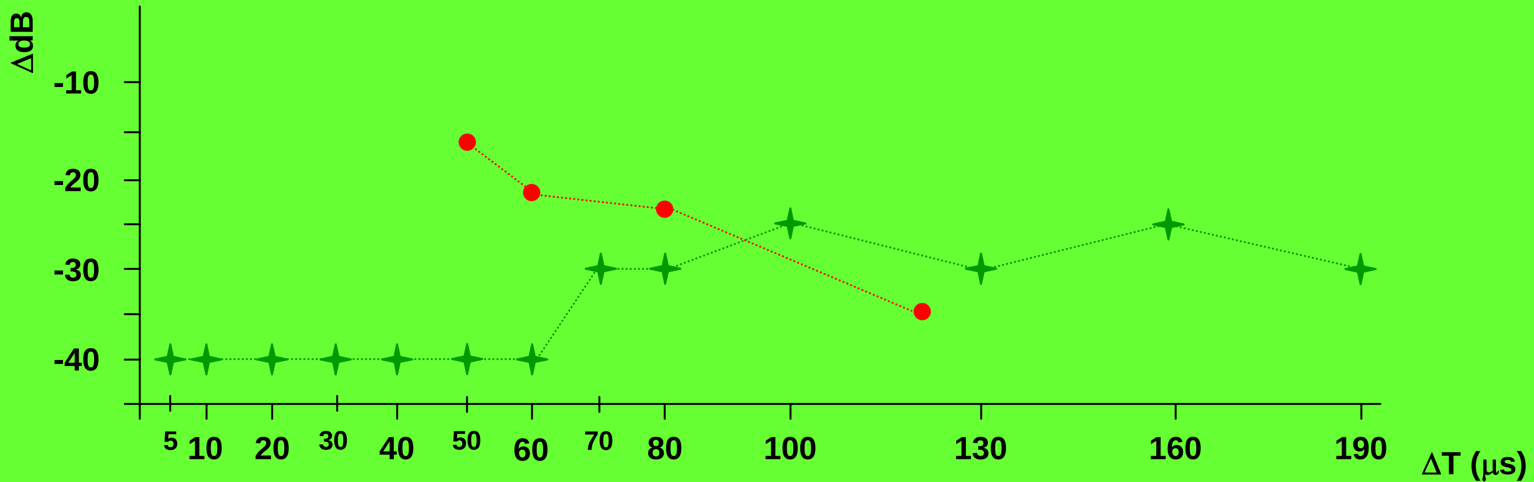


3. Discrimination of synthetic echoes with low-amplitude secondary highlight:

Comparison with the results of the work of D. Helweg, P. Moore, L. Danankiewicz & J. Zafran "Discrimination of complex synthetic echoes by an echolocating bottlenose dolphin"

The signals discriminated by the model differed only in a waveform of the secondary highlights. Both of them (the first and second highlights) were about 30 - 40 μs in duration.

ΔT – the time delay of the secondary pulse relatively the beginning of an echo.
ΔdB – energy ratio between the first and second highlights
Measurements were conducted on a background of white noise of -40 dB *re:* echo's energy, as well as it was in experiments with a dolphin.



Iso-secitivity functions for ΔdB X ΔT, revealed in experiments with a dolphin ( ) and measured in the model ( ).

Here, as well as in previous measurements the maximal sensitivity of the model is limited by 1 μs, which is caused by a step of quantization of system equal to 1 μs. Thereby, the thresholds do not change the values for DT < 60 μs. It is quite presumable to expect improvement of the thresholds in case of decreasing of the step of quantization of the model.

Discussion

1. Summary

We have conducted the measurements of the differential thresholds of the model on the signals well imitating the echoes from actual targets. Herewith we have got the results having definite advantage over those of bottlenose dolphins. Developing the model, we utilized the simplest mathematical interpretation of the data revealed in our experiments just to be convinced in the expediency of continuation of the works in this direction. We suppose that the results obtained testify this expedience.

2. The possible further steps

a) The most effective source of further improvement of the model is its testing on echoes reflected from targets, which recognitions represent urgent practical needs and is inaccessible to underwater recognition by any other means. We just have begun such co-operation with our colleagues in San Diego, namely with Dr Patrick Moore. We expect to receive soon the first results.

b) The other parallel source could be acoustical experiments on beluga whales, which sonar system surpasses that one of bottlenose dolphins, and we still do not know why. The set of tests, which gave us the detailed description of the echo-processing mechanisms in bottlenose dolphins, includes 15 experiments. We suppose that realization of these tests on beluga whales will help us discover the reasons of that superiority.

Appendix 3n

Paul Doust

Blacknor Technology Ltd.

Transducer Equalisation Techniques.

by

Paul Doust

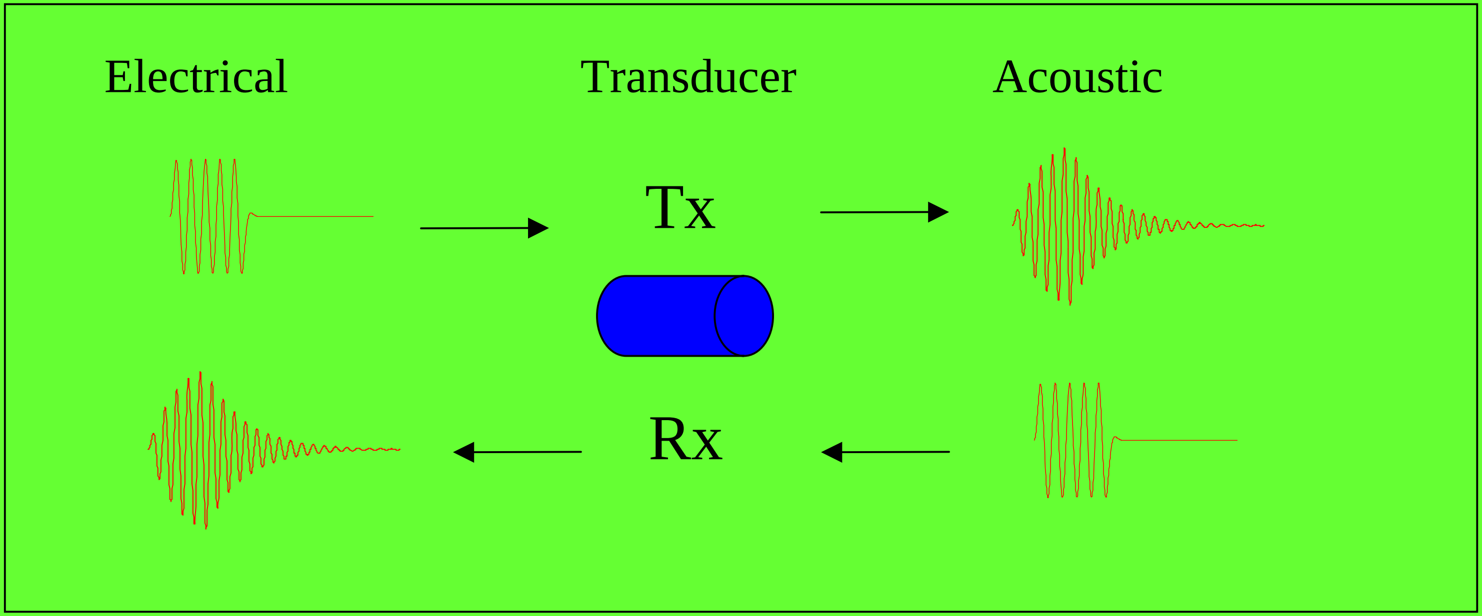
Technical Director

Blacknor Technology

P.E. Doust. Blacknor Technology, Portland, UK. pdoust@blacknor.com

Introduction 1

Problem: The input waveforms electrical or acoustic are distorted by the transducer. *We are trying to pass wide-band signals through narrow-band systems (transducers).*



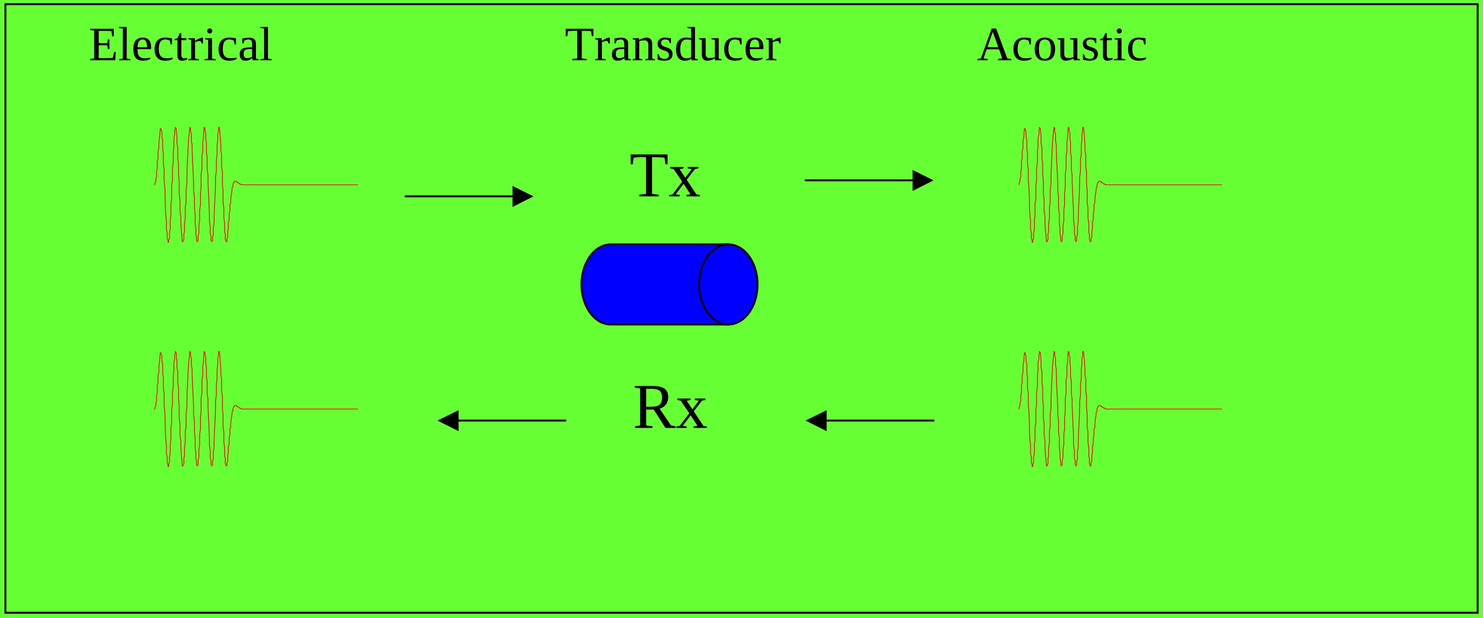
Blacknor Technology Ltd.

Introduction 2

Requirement:

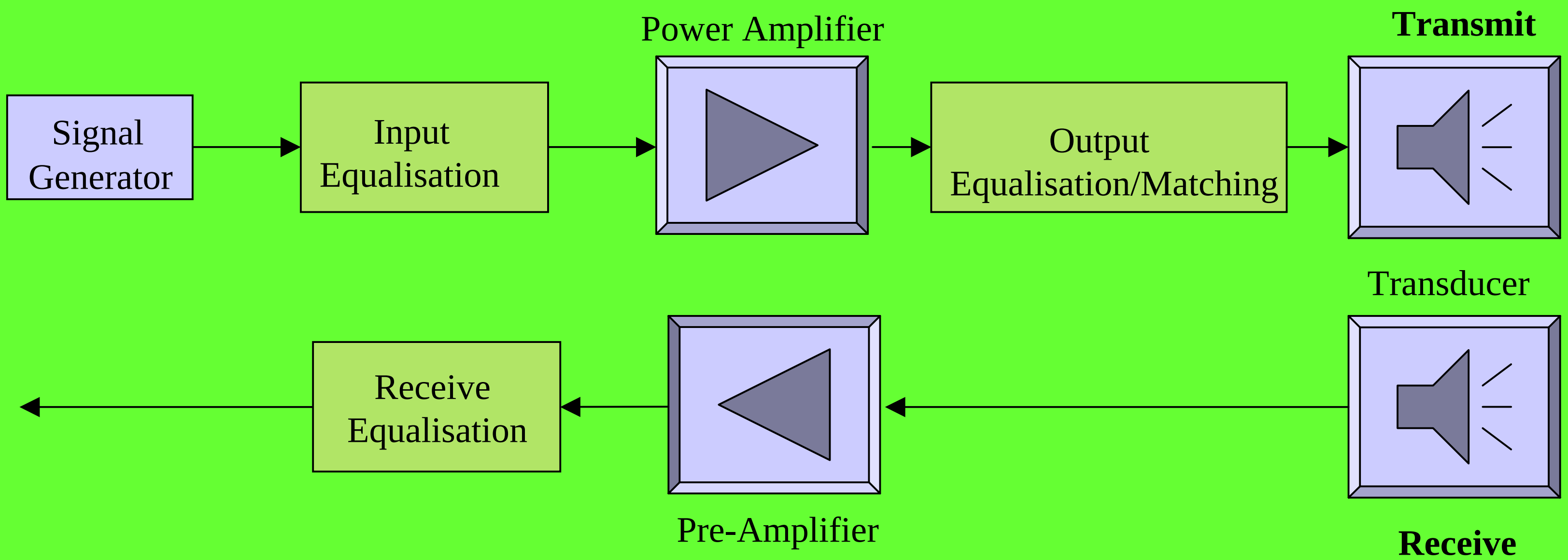
a).To remove the distortion introduced by the transducer on Tx and Rx.

b). Obtain a high level of electro-acoustic efficiency between the power amplifier and the Tx transducer.



Solution

Blacknor Technology Ltd.



1). The importance of the transducer - Critical interface with the water.

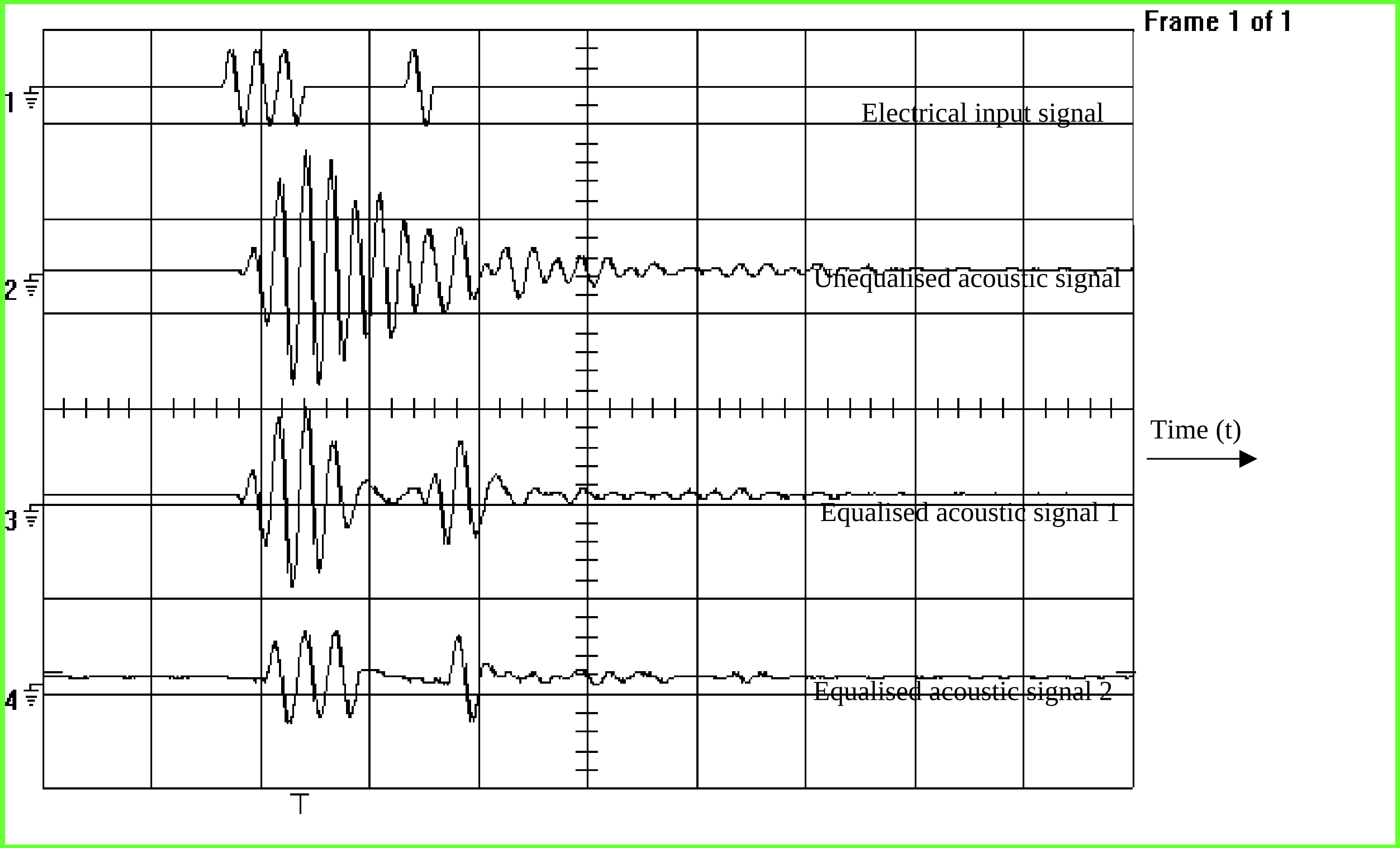
2). The aim is to minimise the distortion caused by the Transmit and Receive Transducer systems using Input and Receive Equalisation to obtain an overall Linear Phase.

3). Optimise the power transfer from amplifier to the transducer when transmitting using non-dissipative Output Equalisation.

4). Of particular interest :- a more accurate observation of the underwater environment.
:- range resolution, bio-acoustic interpretation and measurements.

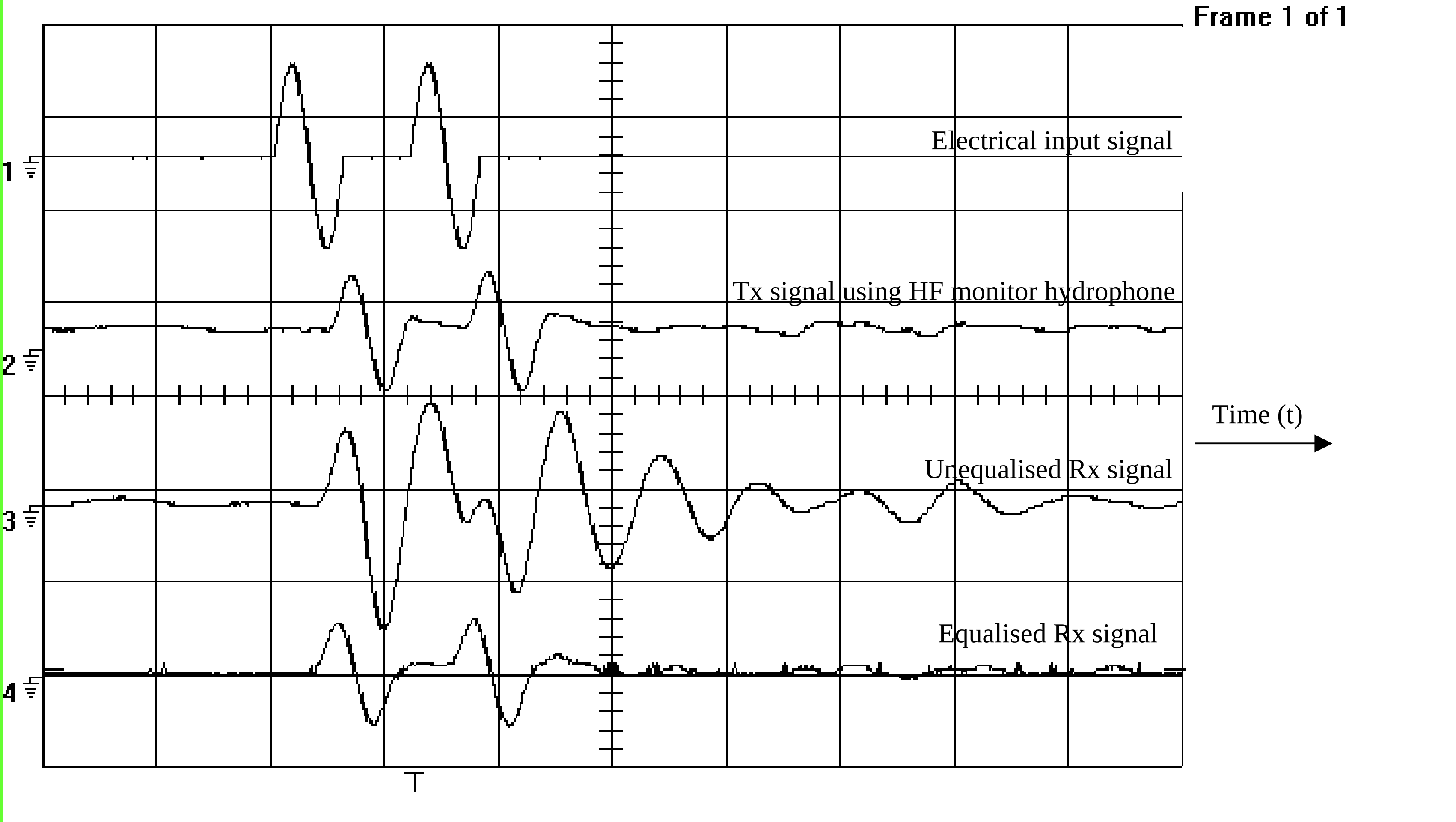
Equalised Transmitter Results

Blacknor Technology Ltd.



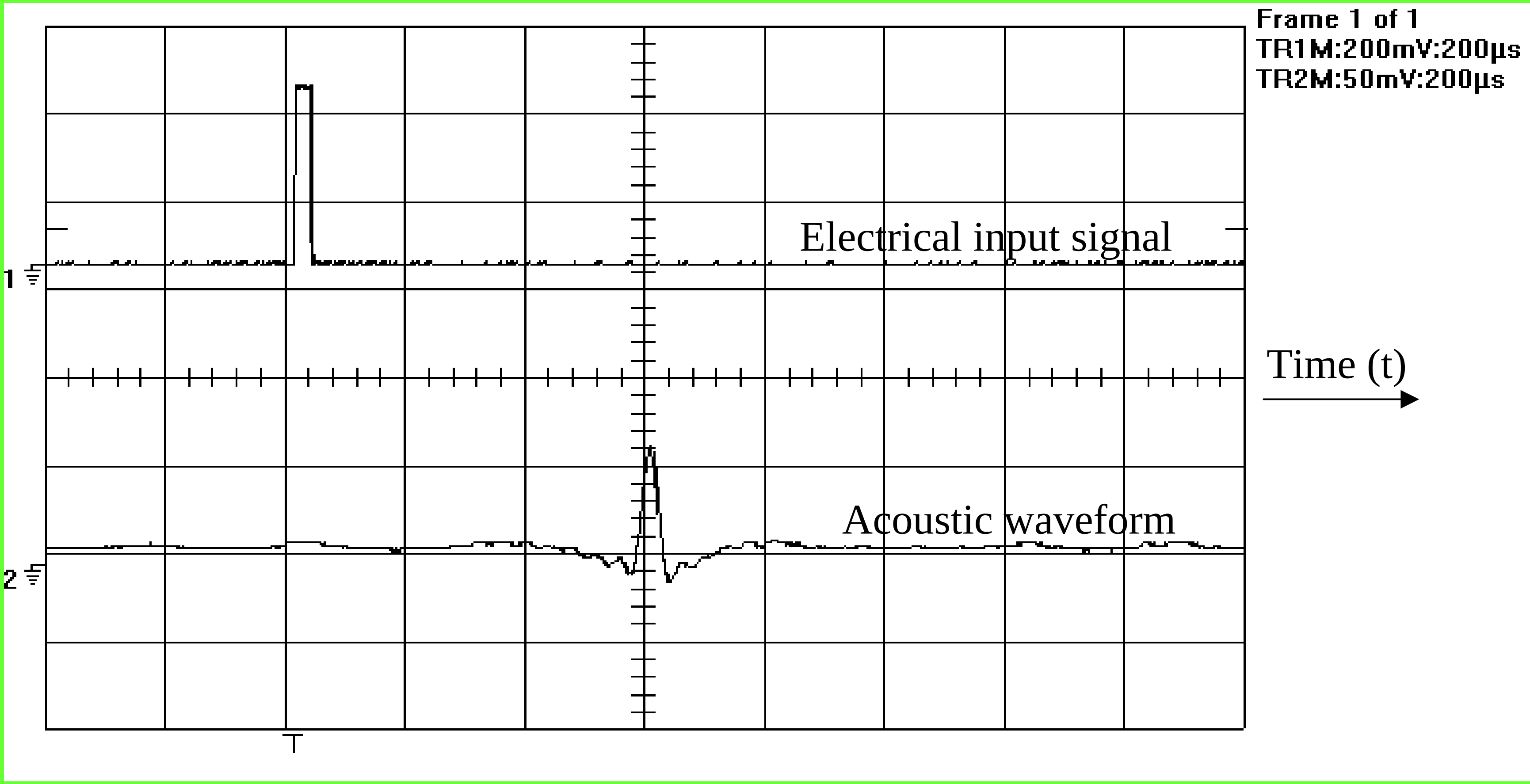
Receiver Equalisation

Blacknor Technology Ltd.



Blacknor Technology Ltd.

Approximation to an Impulse using transmit and receive equalisation.



Summary

Transmitter.

1).Non-Dissipative Analogue Matching Techniques :- **Enables broadband high power transmission.**

2).Short Pulse response **:- Dramatically improved when equalisation techniques are used in conjunction *with 1).***

Receiver.

1). Equalisation techniques :- Needed to remove distortion caused by receiver hydrophone. (especially if the same transducer is used for transmit and receive.)

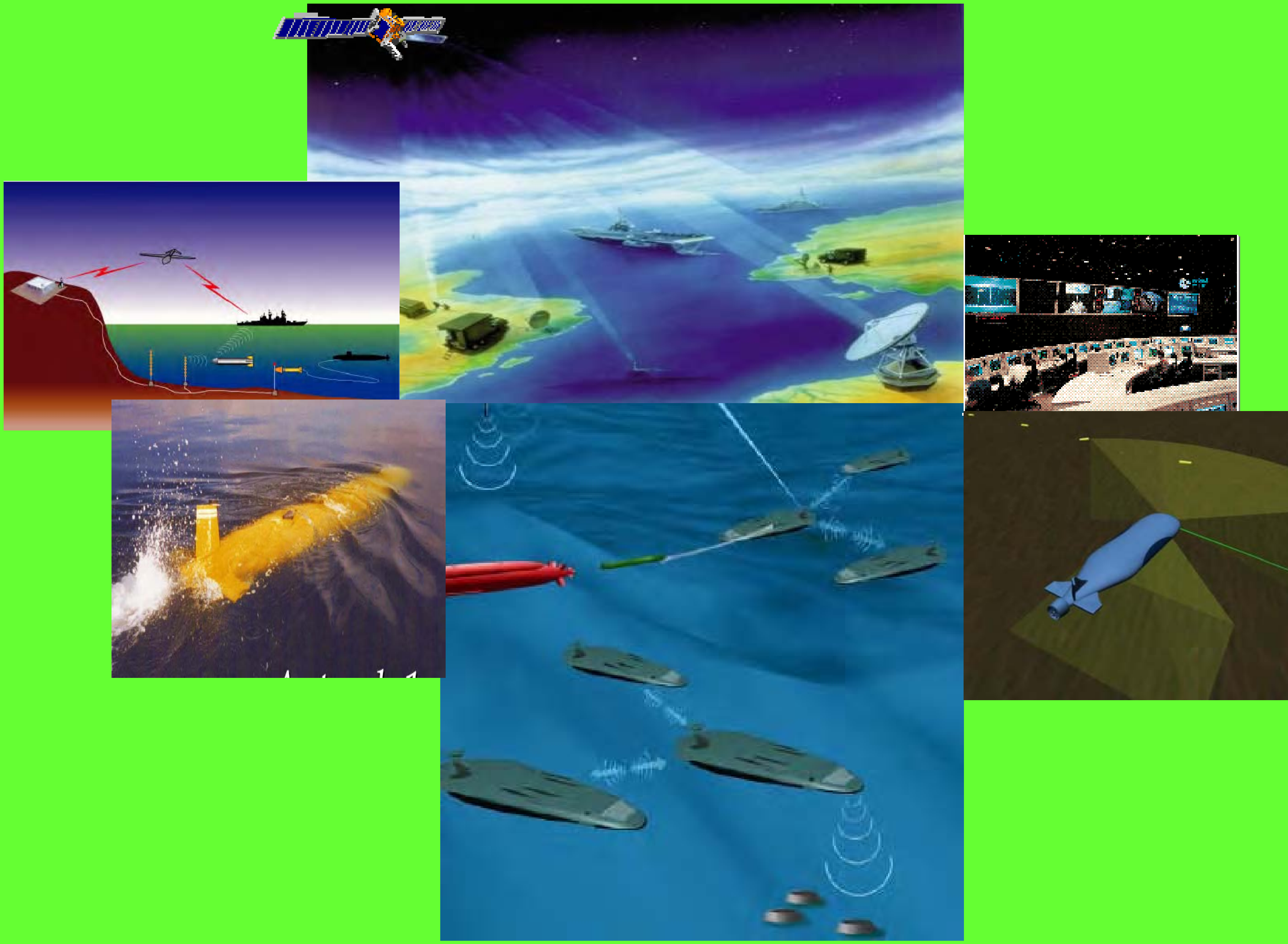
Advantages :- A more accurate measurement of the underwater environment.
Improvement in range resolution.

Uses :- Communications, sonar imaging, non destructive testing, bio-acoustic measurements and interpretation.

Institute of Acoustics, Volume 23, Part2, 2001. P E Doust, Dr J.F.Dix.

Appendix 3o

Matt Geen



Research objective

- To **de-risk** critical UUV technologies and their integration into existing and future Underwater Battlespace platforms
  - Future defined as 2015+
  - De-risking defined relative to Technology Readiness Levels (TRL) 5/6
  - Integration into existing platforms to be defined relative to System integration Readiness Levels (SRL)

Technology Readiness Levels

1	Basic principles of technology observed & reported
2	Technology Concept and/or Application Formulated
3	Analytical and Laboratory Studies to validate analytical predictions
4	Component and/or basic sub-system technology valid in lab environment
5	Component and/or basic sub-system technology valid in relevant environment
6	System/sub-system technology model or prototype demo in relevant environment
7	System technology prototype demo in an operational environment
8	System technology qualified through test & demonstration
9	System technology ‘qualified’ through successful mission operations

Low

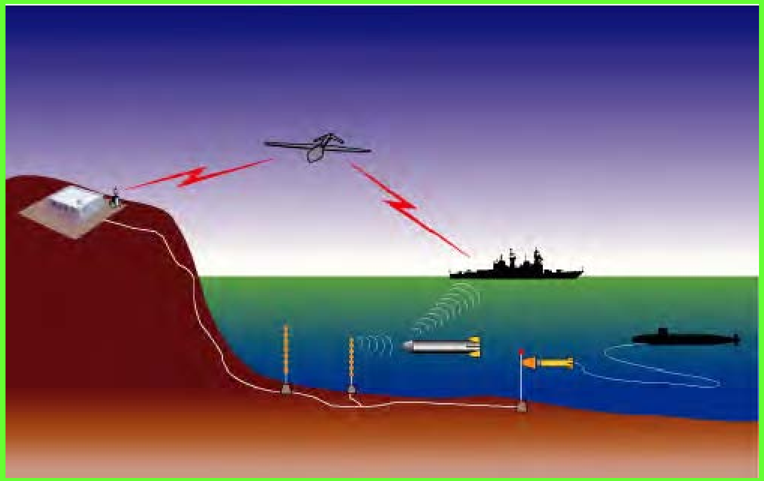
Medium

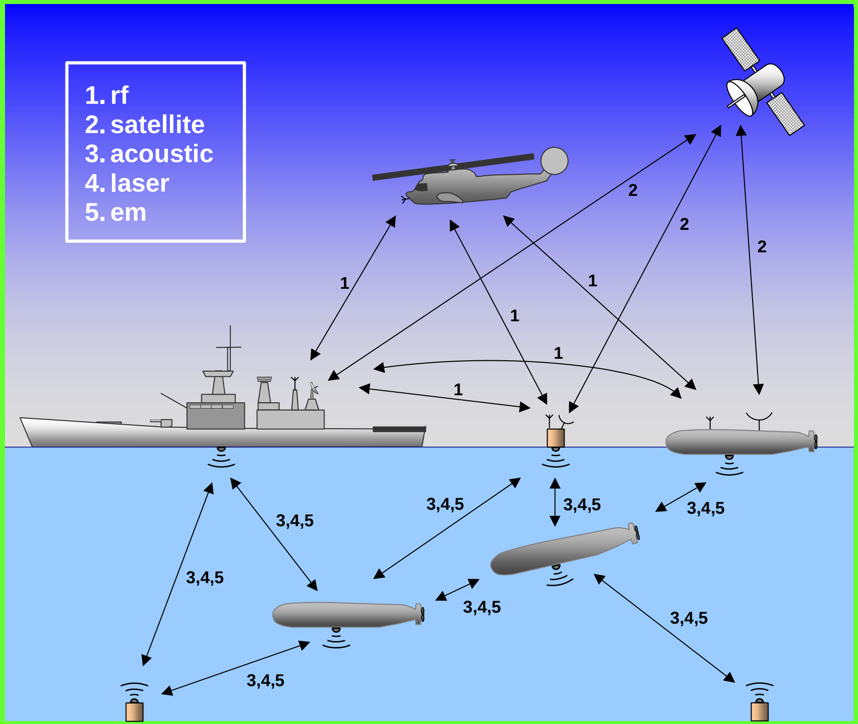
High

Increasing Maturity

Key Technology areas

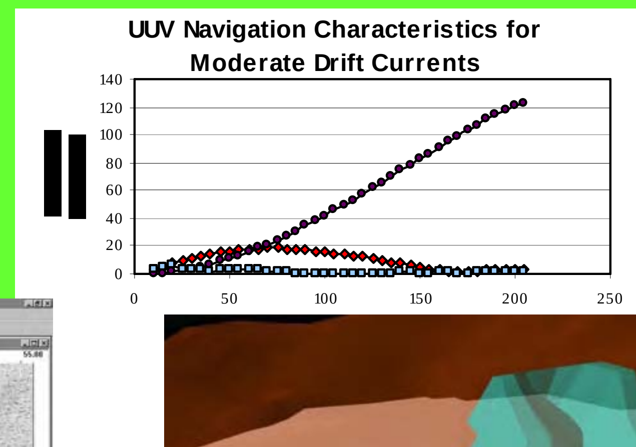
- Communications
- On-board Data Logging

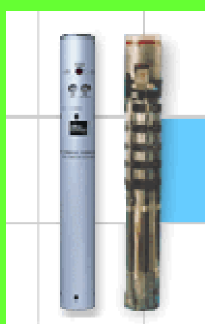


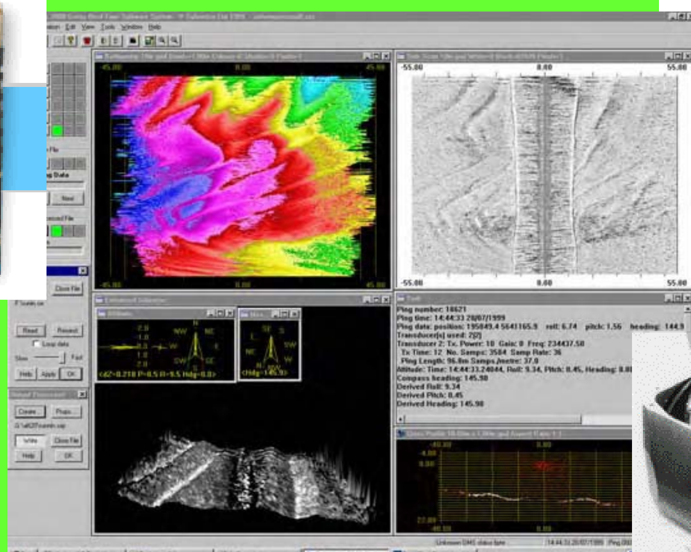


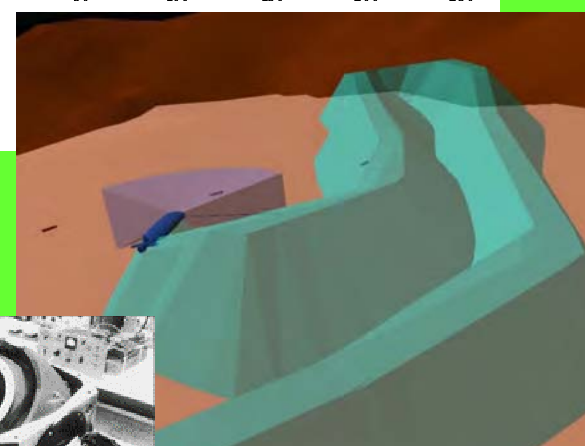
Key Technology areas

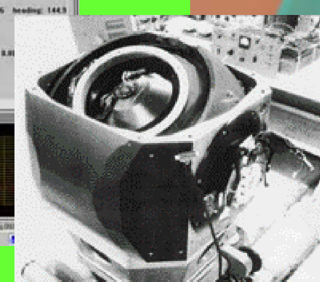
- Navigation
- Payloads & Sensors





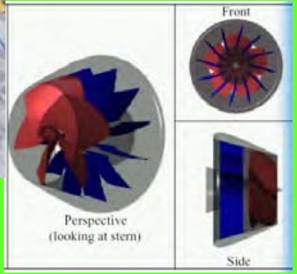


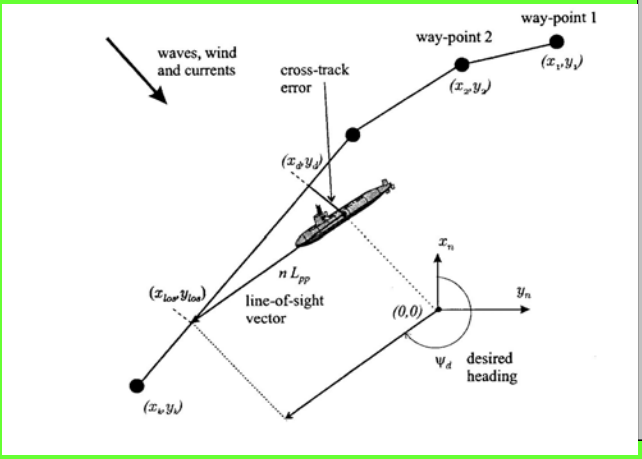


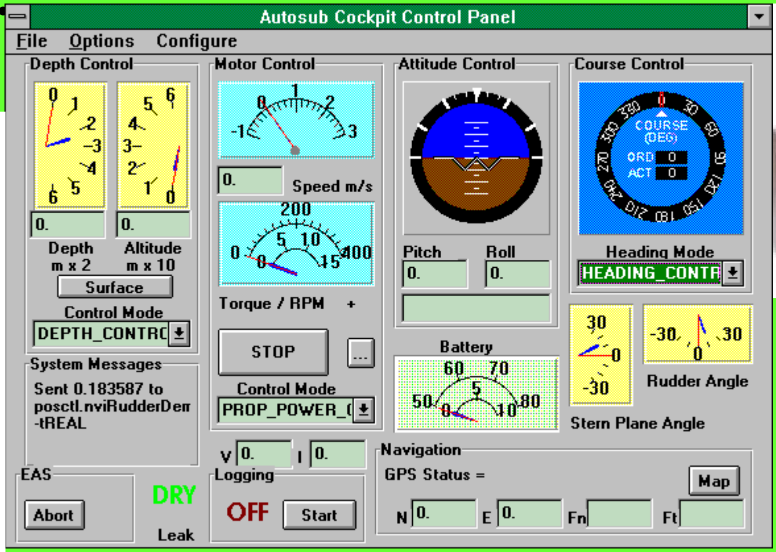


Key Technology areas

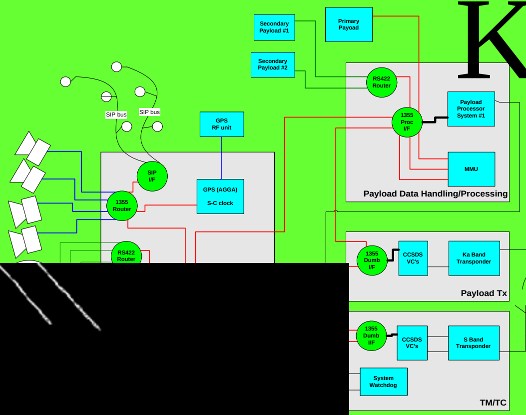
- Energy Storage and Propulsion Systems
- Command, Control and Mission Mgmt.

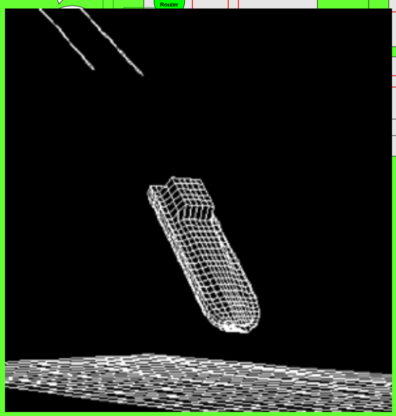





Key Technology areas





- BAUUV Design and Integration
- Platform Integration *(incl. launch & recovery)*

Industry Team

Providing independent and innovative thinking drawing on heritage from experience in Marine, Battlespace, off-shore oil/gas and Academic domains

Prime Contractor

Systems Engineering & Assessment Ltd.

Major Subcontractor

- Scientific research
- Autosub development

Major Subcontractor

- Operators of 24 vessels and 117 ROVs in off-shore oil/gas
- Geosub development

Plus 'best of breed' technology experts

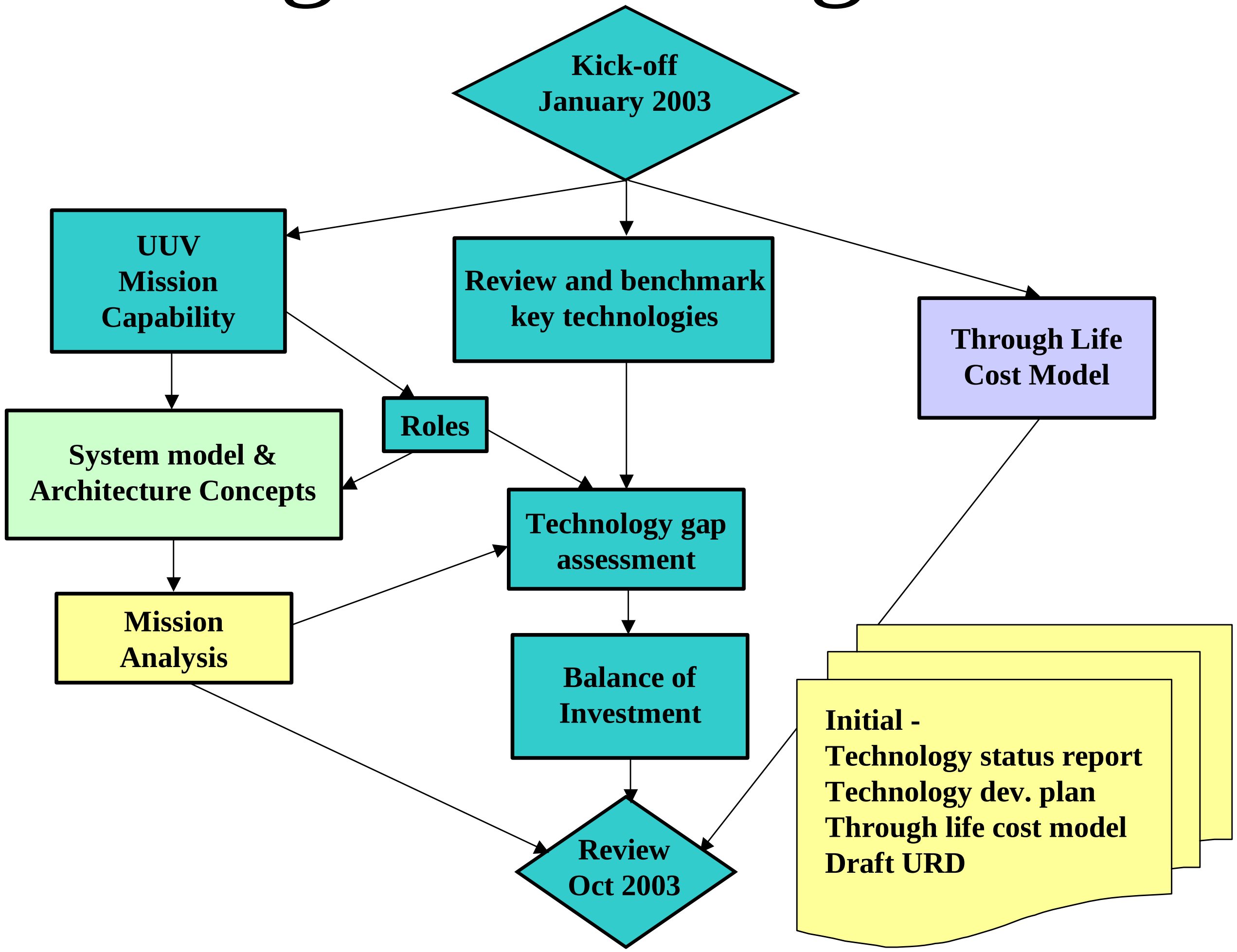
Best of breed Technology experts

1. Newcastle University
2. University of Plymouth
3. Toumaz Tech. Ltd
4. Roke Manor Research
5. Stirling Dynamics Ltd.
6. Heriot-Watt Uni./SeeByte
7. Flight Refuelling Ltd.
8. Devonport Royal Dockyard
9. Frazer-Nash Consultancy
10. Ultra-Electronics Ltd.
11. UWE
12. Insys Ltd.
13. QinetiQ
14. Fortkey
15. CODA Technologies.
16. AEA Technologies.
17. Oxford Technologies.
18. Wellman Ltd.
19. UWCN
20. Rolls Royce Plc.
21. Chelsea Technology Group
22. Cogent DSN
23. MoD(DSTL)
24. Intelligent Energy Ltd.
25. **Plus others**

Best of breed Technology experts – Intl.

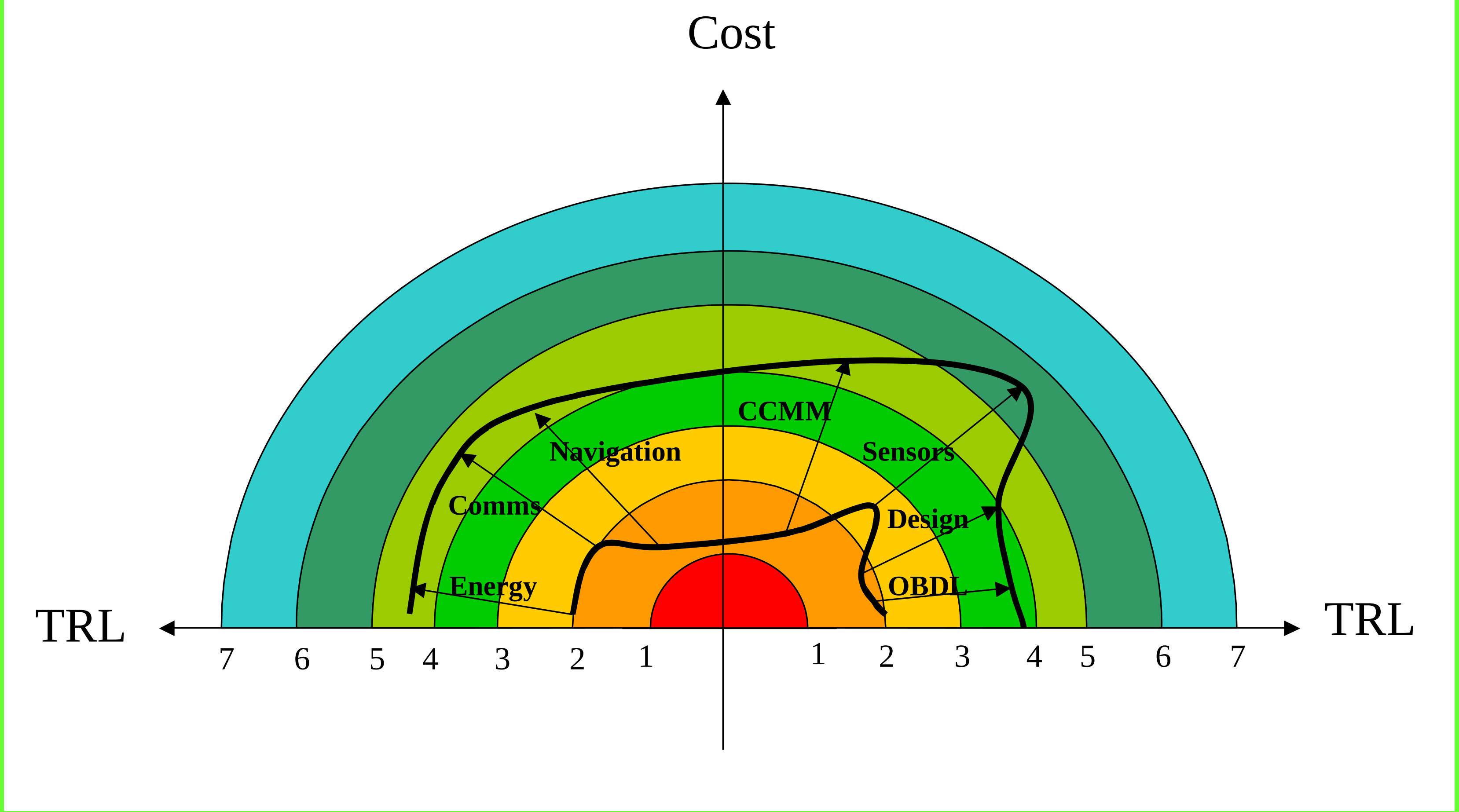
25. Northrop Grumman
26. Sonatech
27. NUWC
28. Johns Hopkins University
29. ECA
30. Thales
31. + more being consulted

Programme Logic – Phase 1

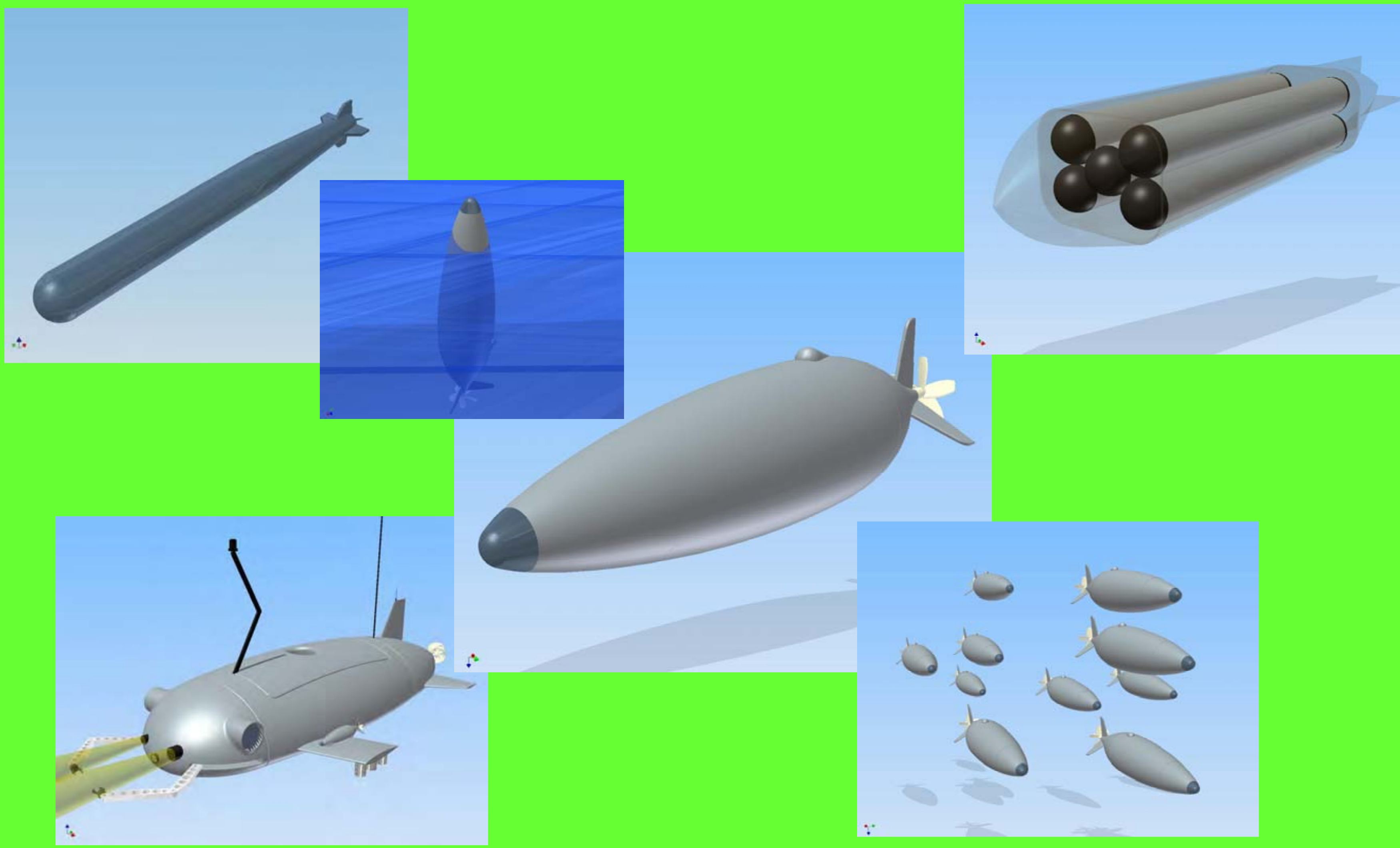


Systems Engineering Approach

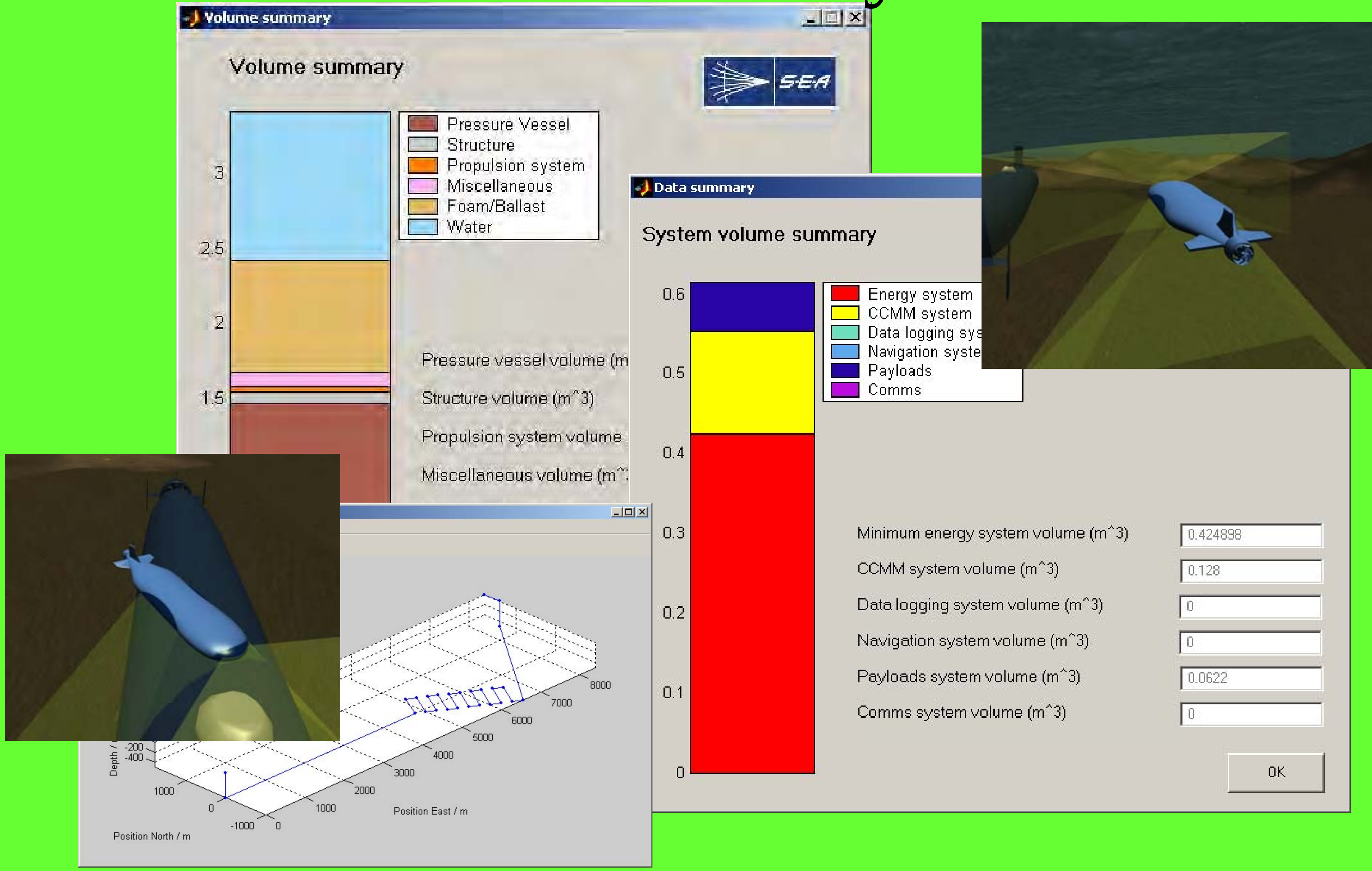
Balance of Investment



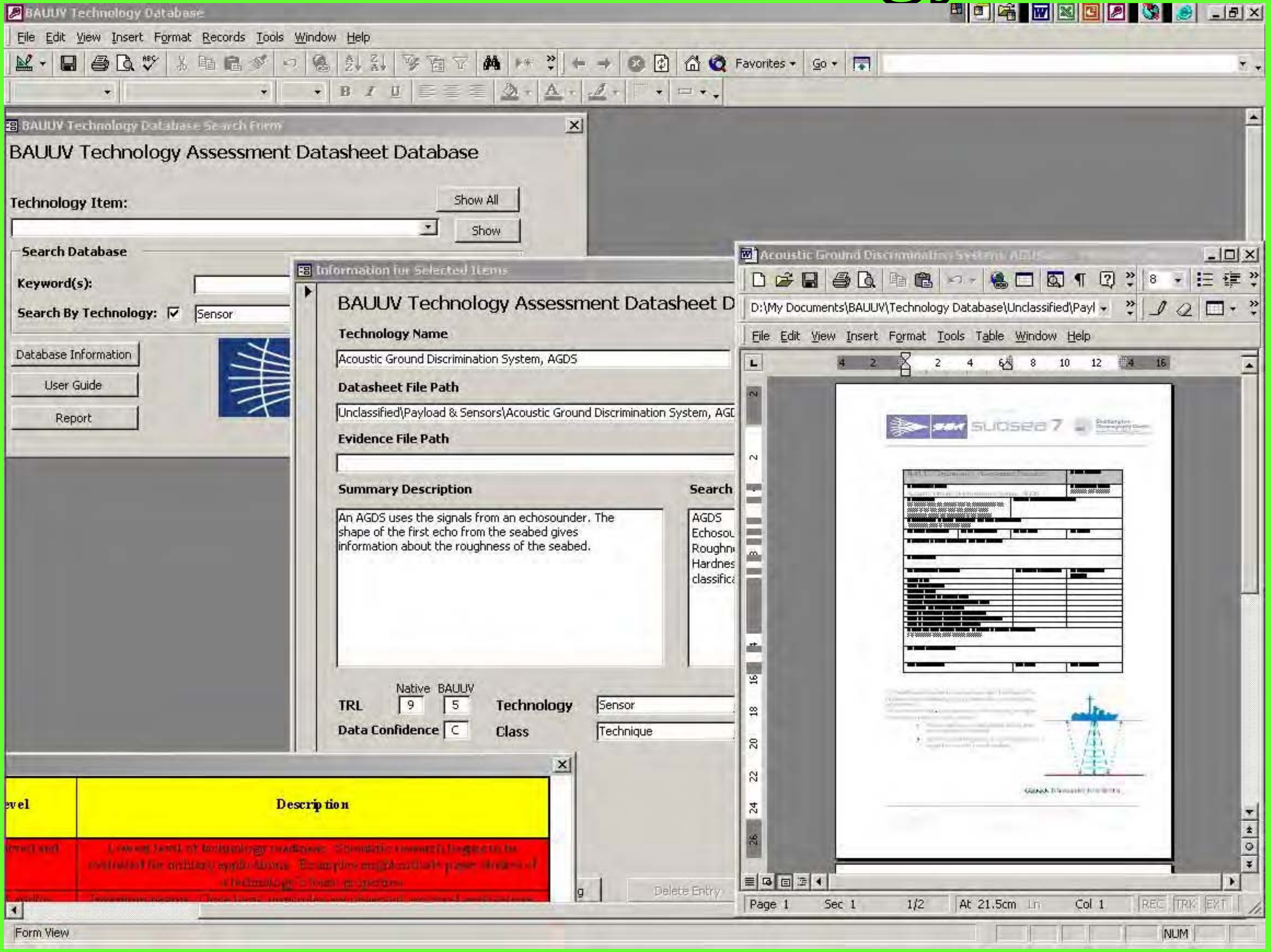
System Options



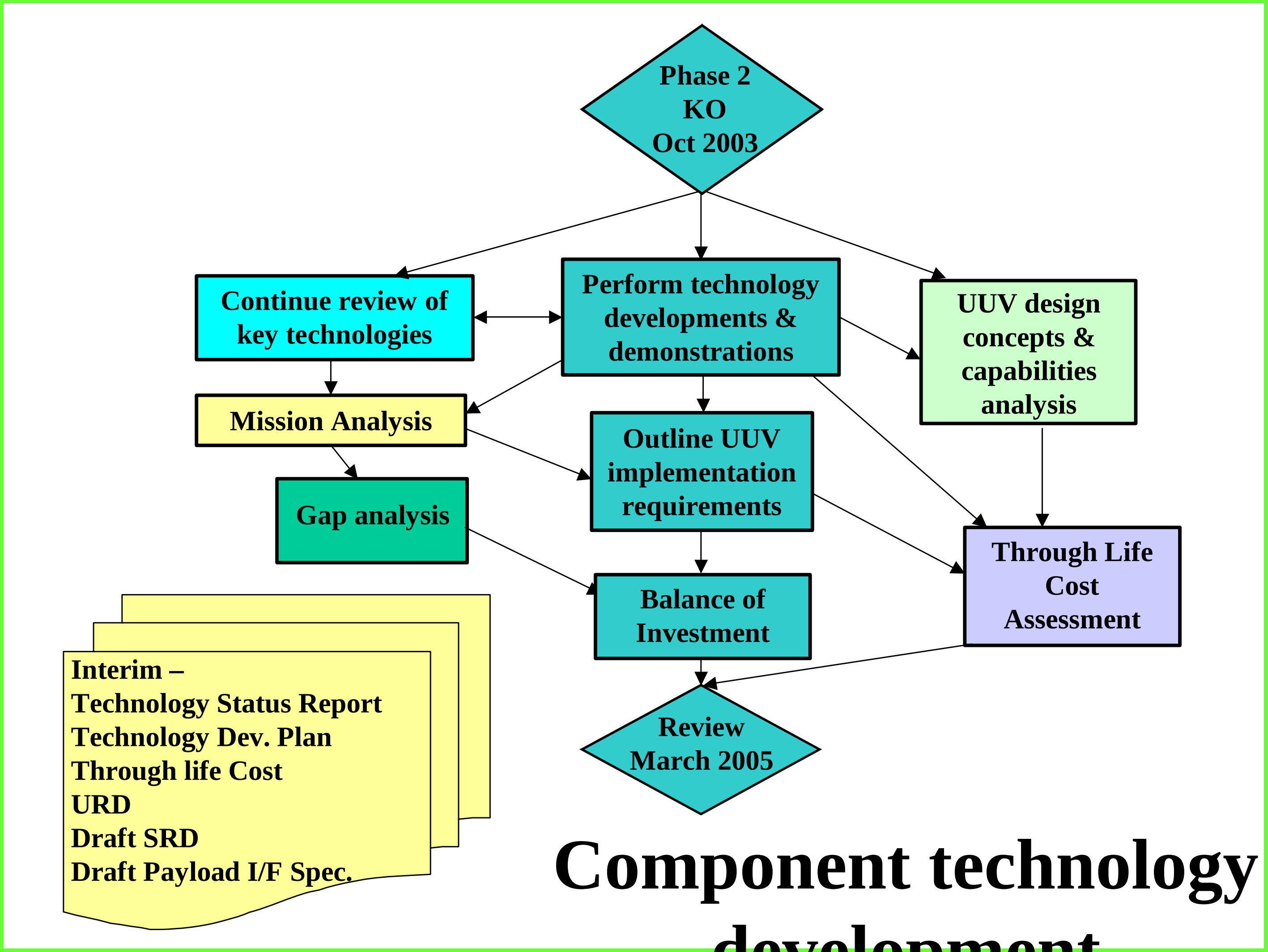
System Model



Technology Bank

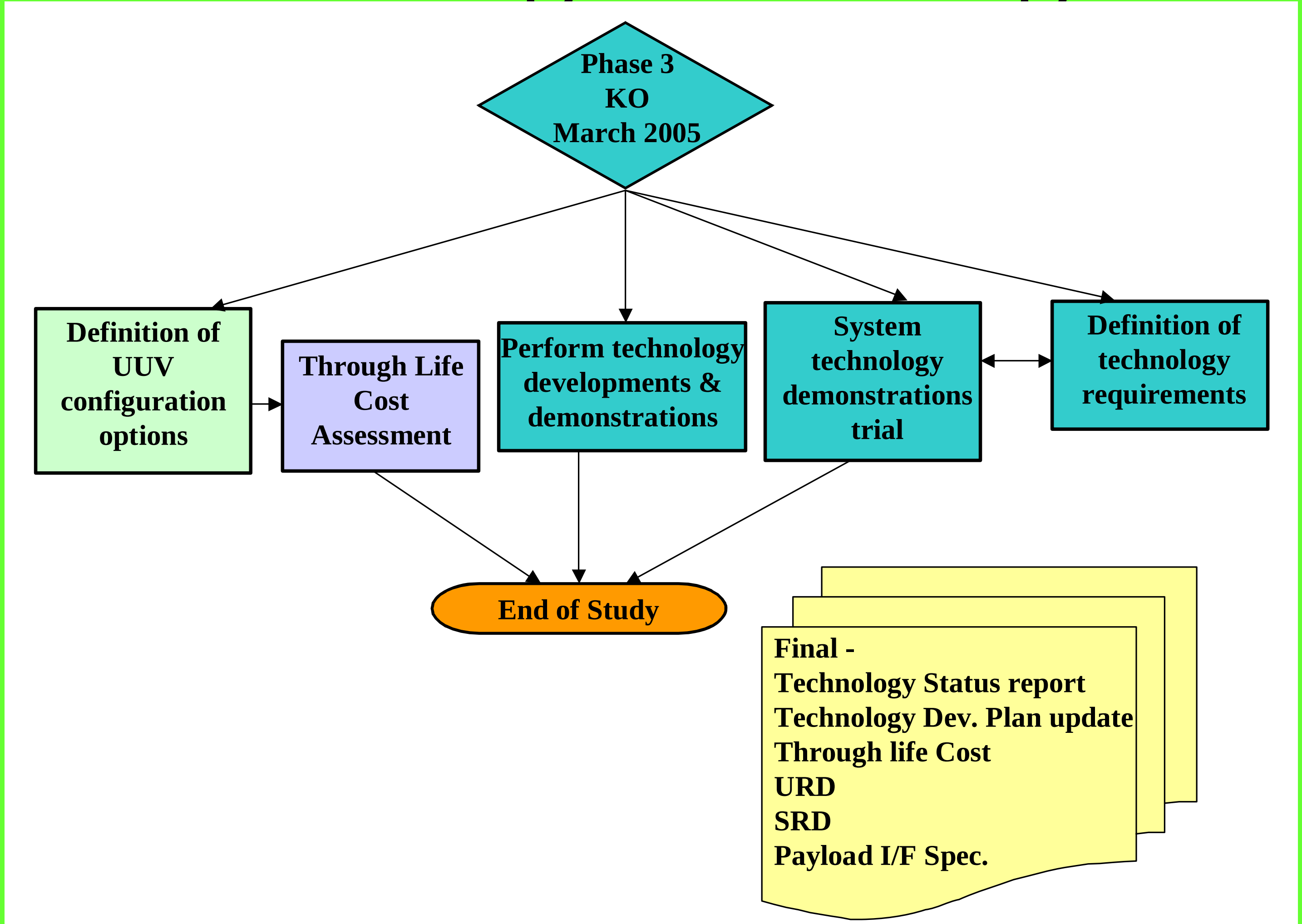


Programme Logic – Phase 2



Component technology development

Programme Logic – Phase 3



BAUUV System definition

Major deliverables

- De-Risked Technology Bank
  - Technology data
  - TRL Status + supporting evidence (subjected to QA)
- Document of User Requirements
- System Requirements Document
- Payload Interface Specification
- BAUUV architectural design options
  - Associated Launch & Recovery options
- Through Life Cost assessment (future operational fleet)
- Technology Development Plan (current + future)

TOOLBOX of TECHNOLOGY OPTIONS

Technology Development summary

- Key technologies readiness to be demonstrated, relative to the TRL 5/6
- Leveraging and parallel developments for inputs to the Technology Bank
- Component technologies that are ready to be spun-off to provide an early capability

Applications of Bioacoustics

- Communications
- Object avoidance
- Area surveying:
  - Bathymetry
  - Mine countermeasures (MCM)
  - Sub-bottom

Advantages of Bioacoustics

- Stealth:
  - Low power
  - Bio-mimicing: sounds like natural noise source (but have to be geographically realistic!)
- Higher resolutions
- Higher bandwidths
- Improved ranges

Bioacoustics for BAUUV, Summary

A BAUUV has a similar task and challenges to a marine creature:

- Find targets of interest: mid water, and under the seabed
- Communicate with friends
- Safely navigate the environment
- Don’t get caught up in obstructions
- Don’t get found by things that want to eat you!

They currently do that a lot better than we can!

Appendix 3p

Dick Waters

Echolocation in the Egyptian fruit-bat *Rousettus aegyptiacus*

Dr Dean Waters
School of Biology
University of Leeds

Bats of the world….

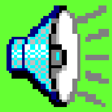
- 813 species of microchiroptera
- 173 species of megachiroptera

- ALL microchiroptera echolocate
- NO megachiroptera echolocate..except…the genus *Rousettus*

Rousettus aegyptiacus

Their echolocation system

- Sounds produced by clicking the tongue
- Pairs of pulses are produced
- One pair of pulses produced every wingbeat cycle



How good is it?

Griffin et al. (1958) suggested that the echolocation system of *R. aegyptiacus* was as good as that of a microchiropteran

However…...

How good is it?

However, not everybody agrees:

‘rudimentary’

‘simple’

Aims:

- To repeat Griffins 1958 experiments but with a statistically valid number of animals
- To look at the call structure in more detail

14 x 2.5 x 2.5 m flight tunnel

Avoid wire obstacles

Spacing = 53 cm

Wingspan = 61 cm

Treatments

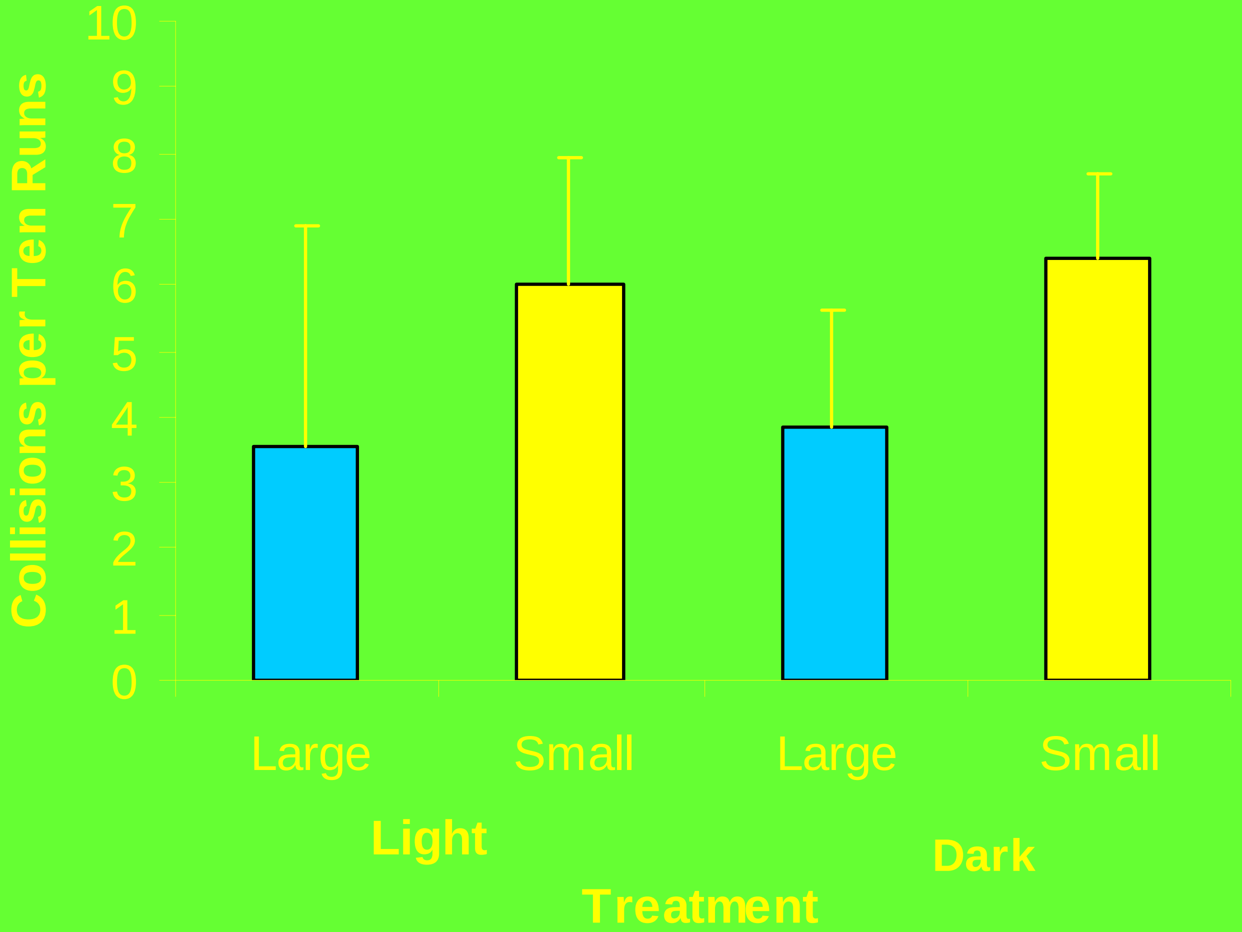
	6 mm dia.	1.3 mm dia.	Control
Posn. 1	5 runs	5 runs	10 runs
Posn. 2	5 runs	5 runs	

Repeated in light conditions and complete darkness

Predictions

- Large wires should be more ‘detectable’
- Collision rate should go up in the dark
- Detection of the small wire should be proportionately more difficult in the dark I.e there should be an interaction between ‘light condition’ and ‘wire diameter’

Results



Collisions per Ten Runs
10
9
8
7
6
5
4
3
2
1
0
Large
Small
Large
Small
Light
Dark
Treatment

Results of ANOVA

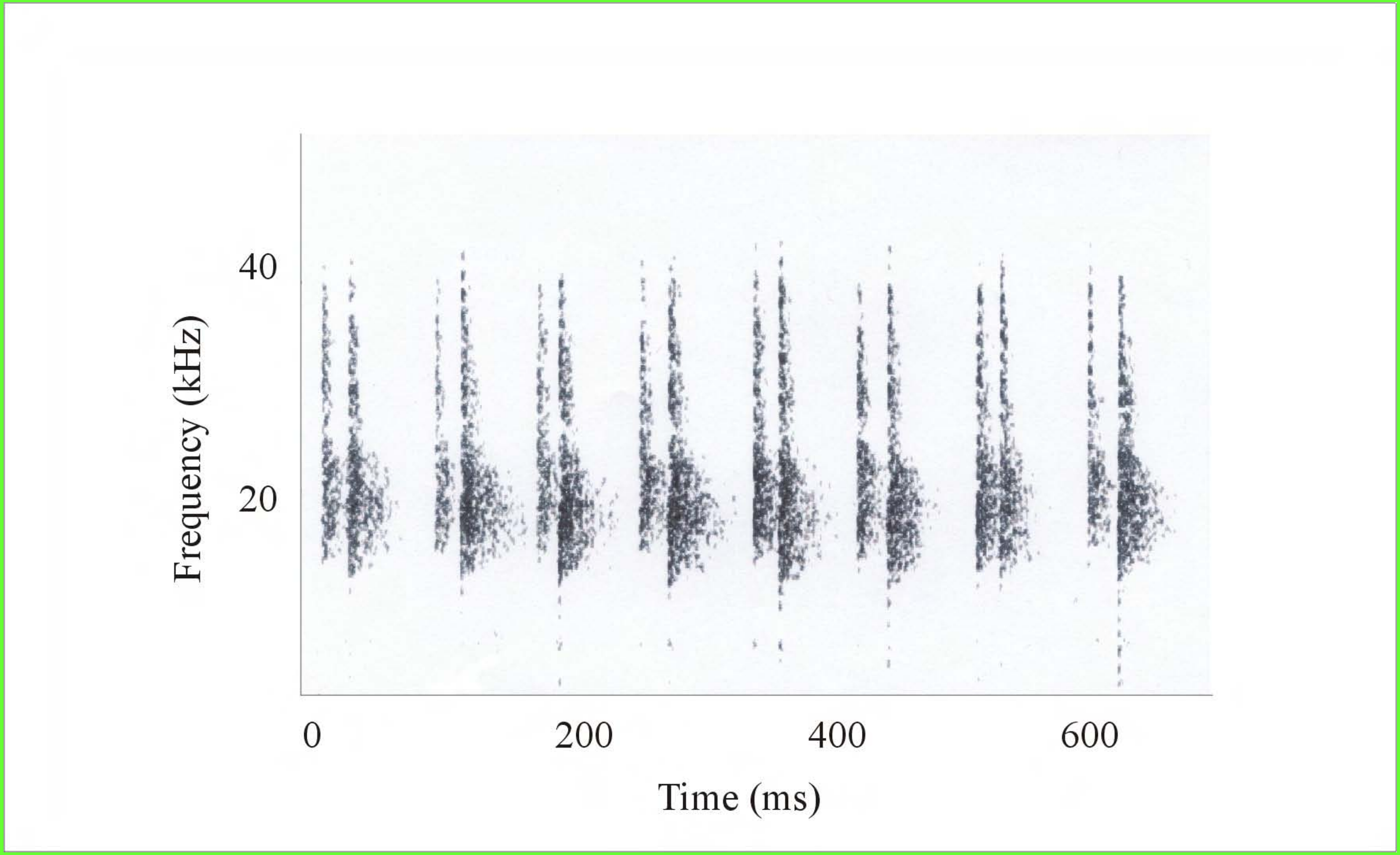
- Factor of ‘wire diameter’ $p < 0.05$
- Factor of ‘light condition n.s.
- Interaction term n.s.

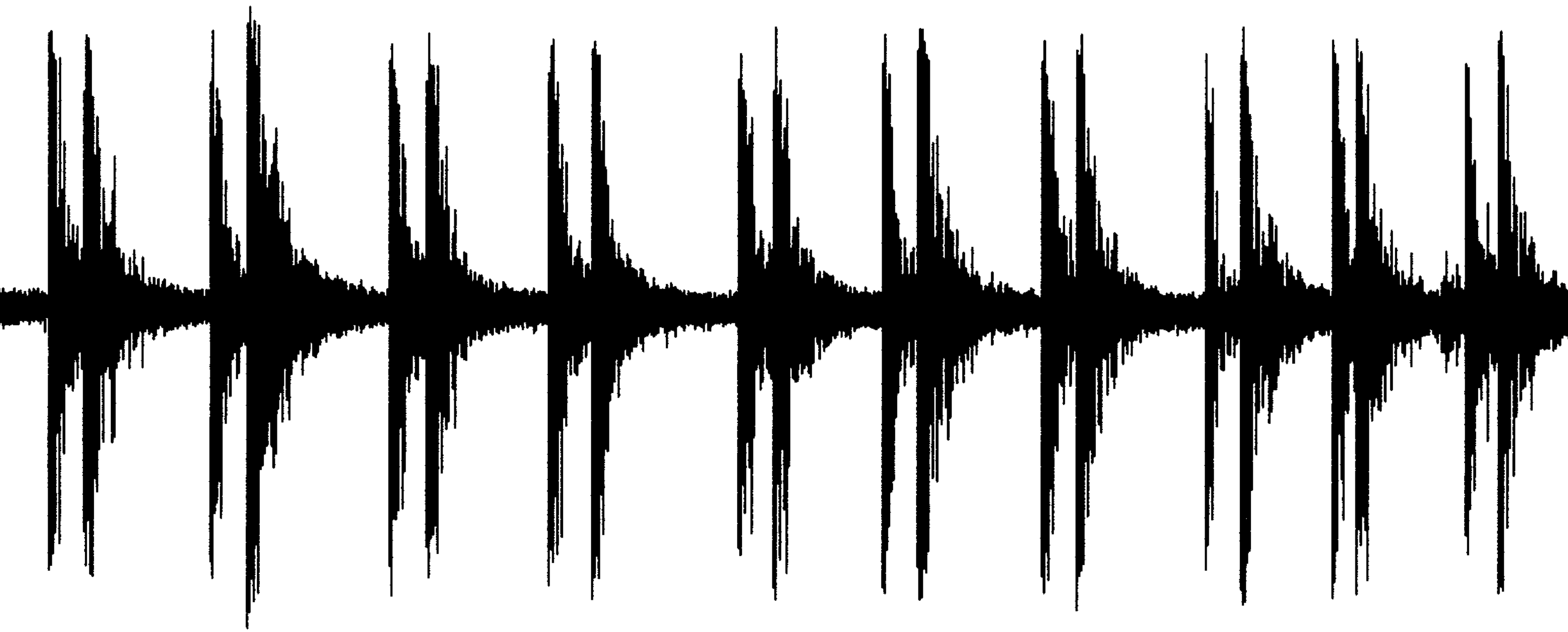
We would expect bats to collide c.80% of the time based on their mean wingspan

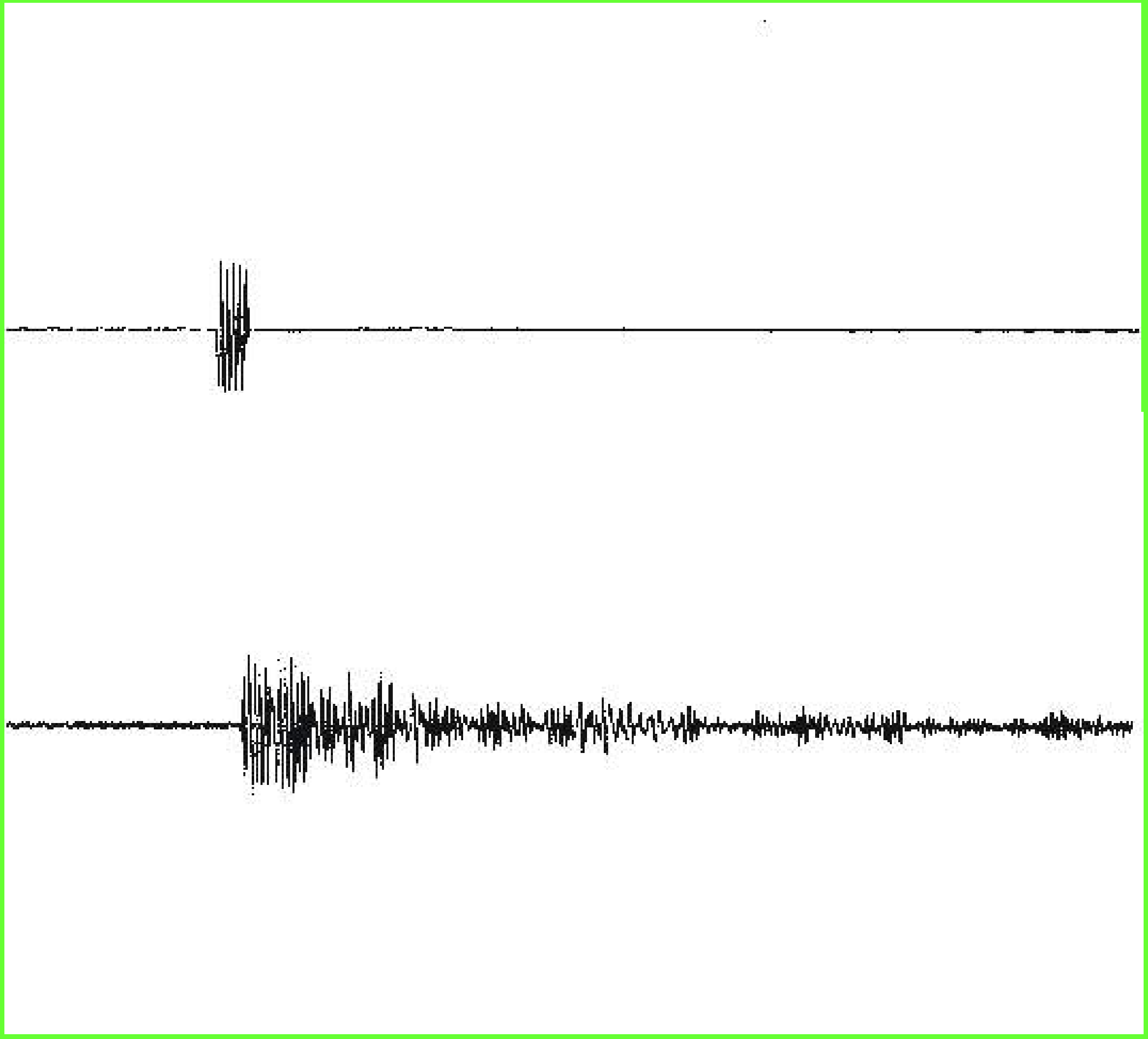
Conclusions

- Bats can detect and avoid the 6 mm diameter wires
- The 1.3 mm diameter wires appear to be just detectable (or the bats can’t be bothered to avoid them
- Light condition has NO EFFECT on collision

Call structure

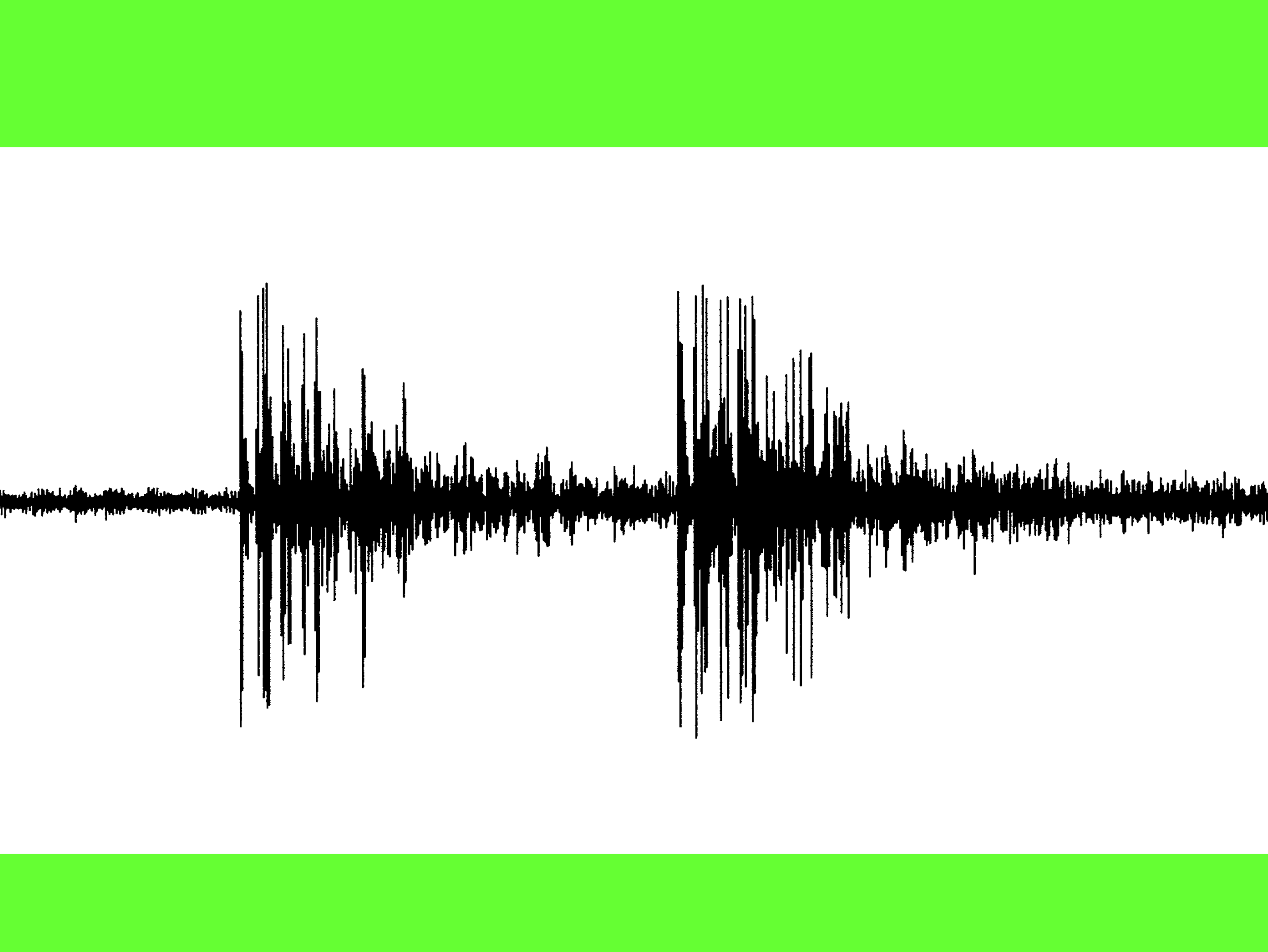


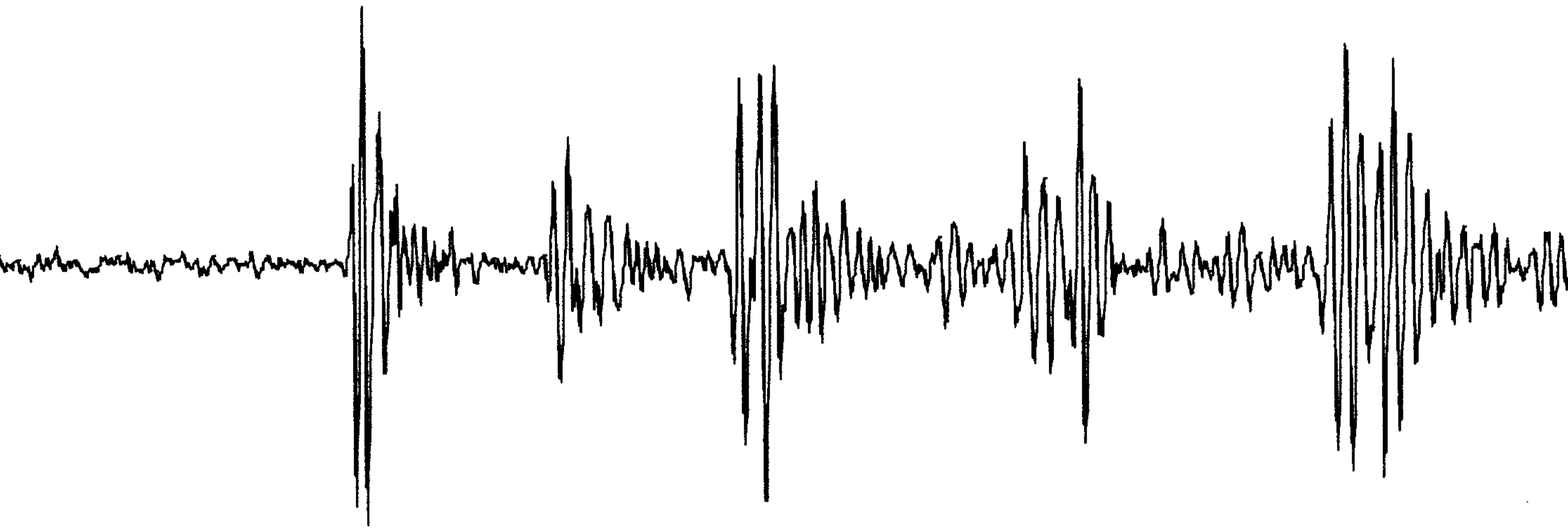


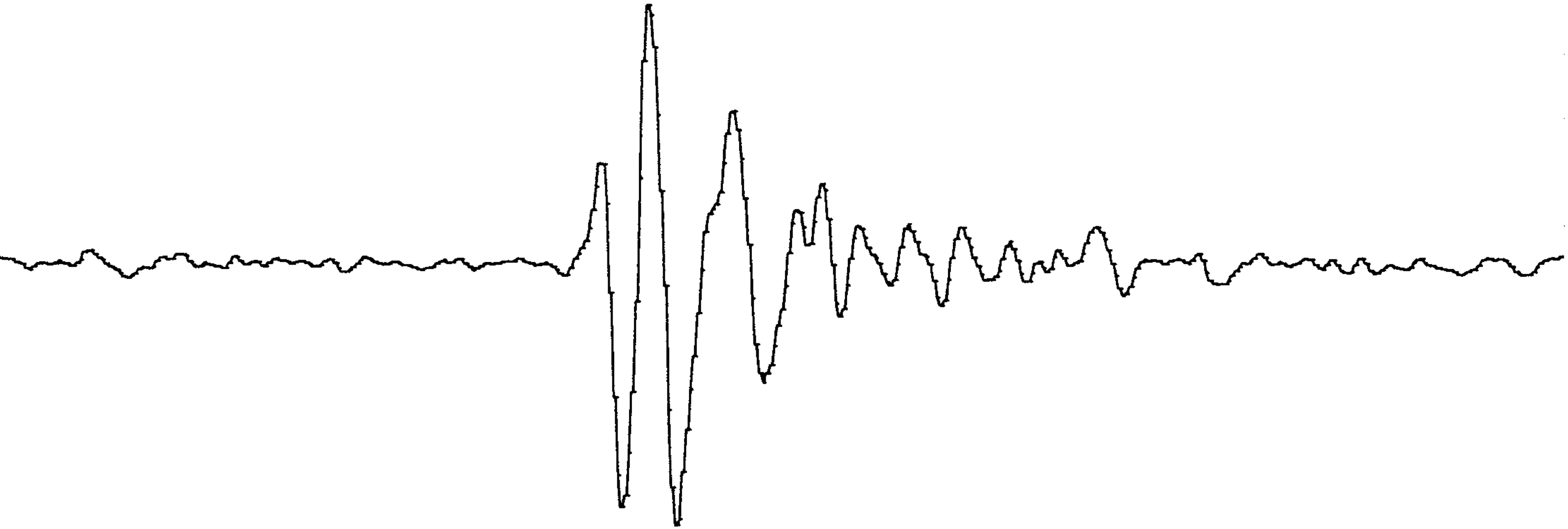


Direct

Indirect





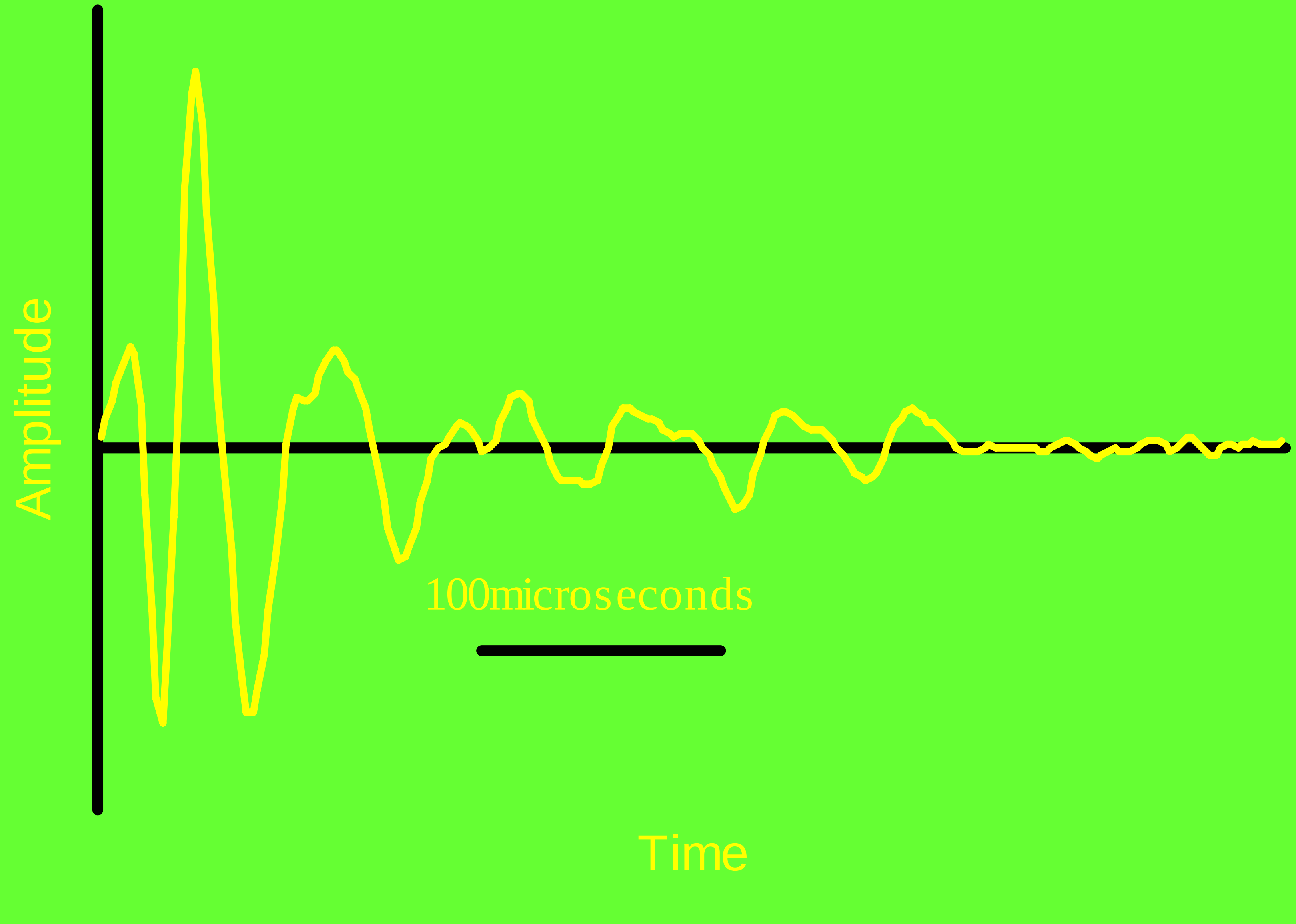


‘True’ call structure

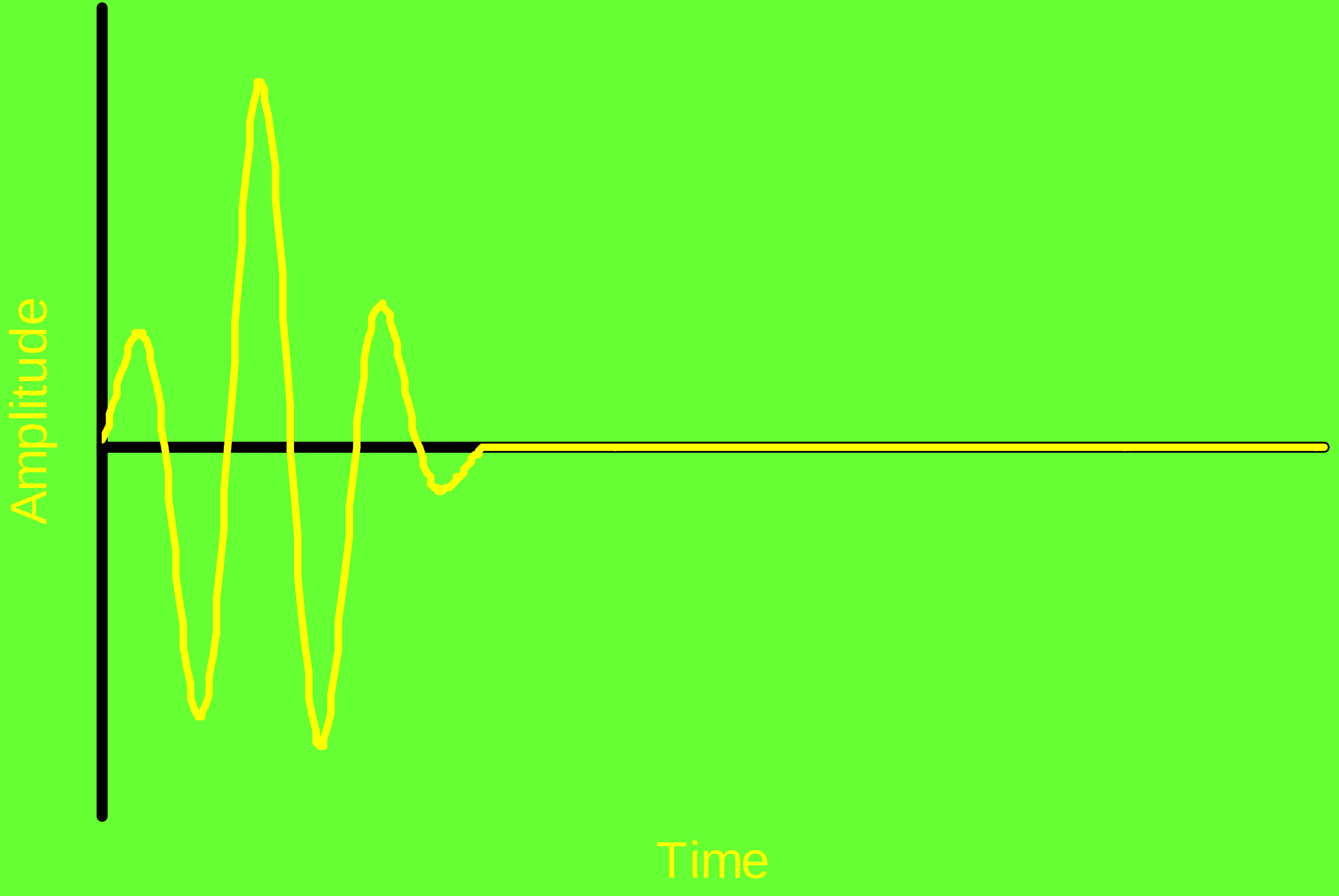
50 calls were averaged

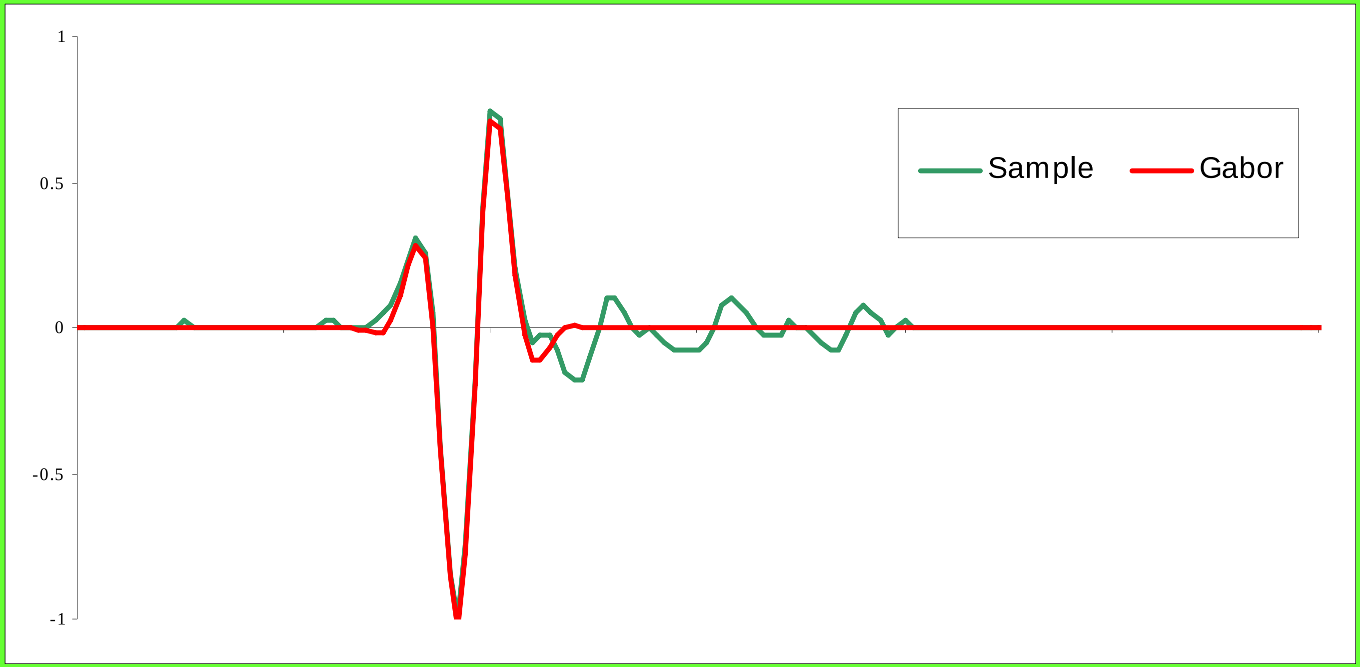
Averaging removed the noise and echoes from the sides of the flight tunnel

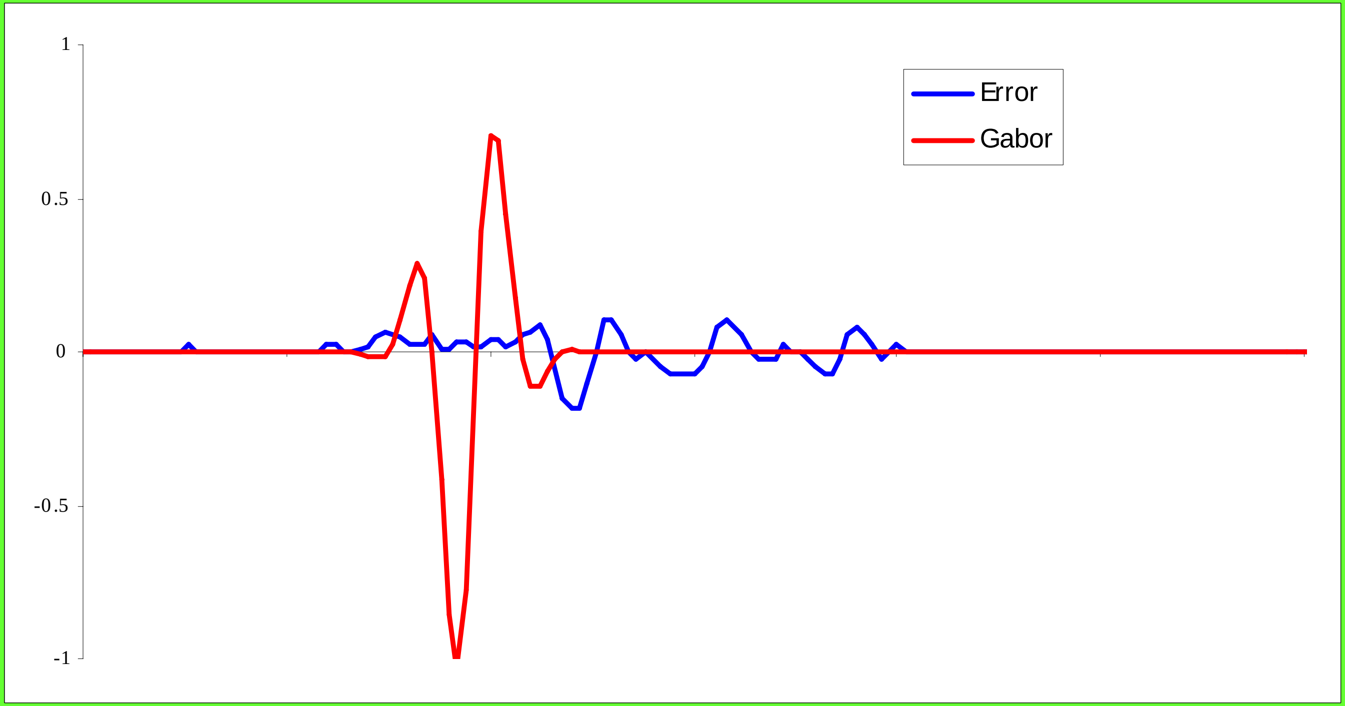
Peak frequency and duration were extracted


Amplitude
100microseconds
Time

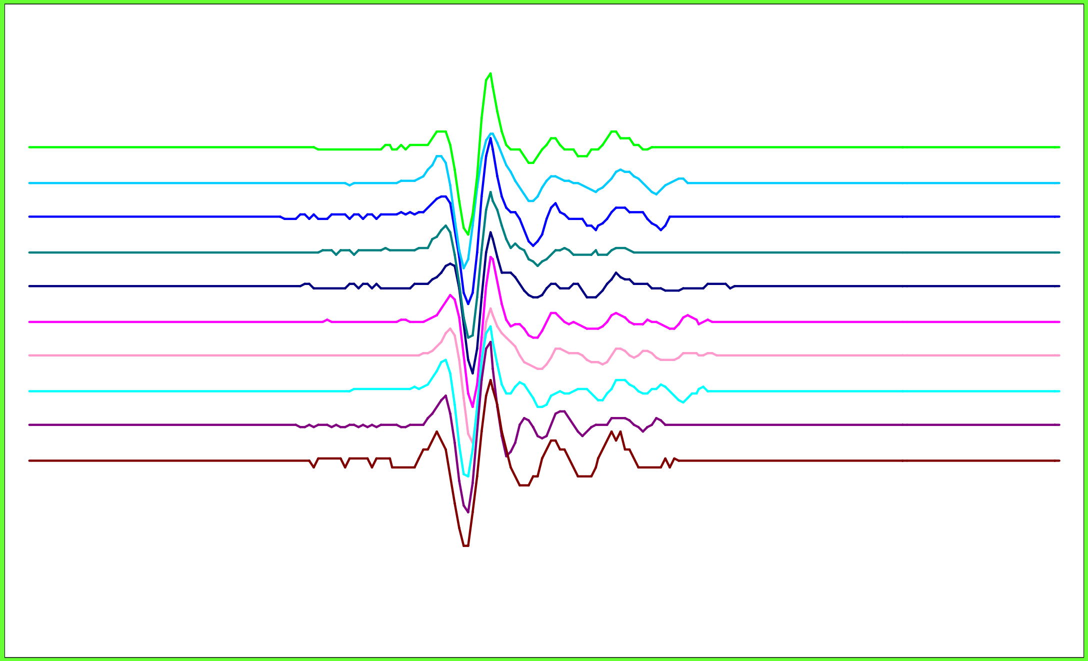
A Gabor function



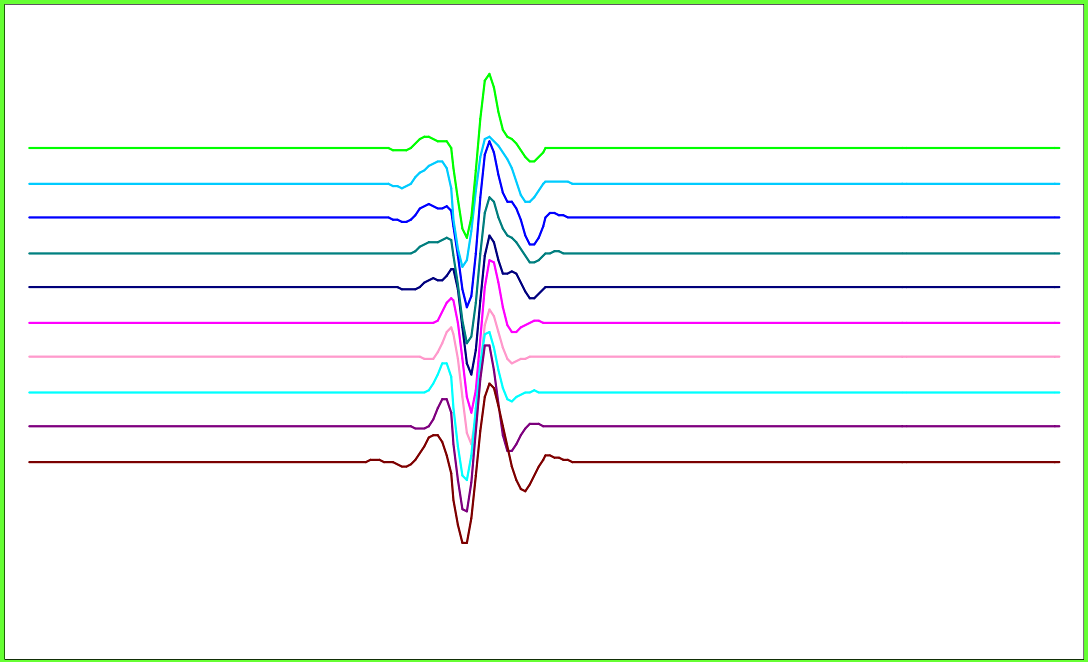

1
0.5
0
-0.5
-1
Sample
Gabor


1
0.5
0
-0.5
-1
Error
Gabor

Real Calls



Gabor models



Conclusions

- *R. aegyptiacus* is much better at detecting obstacles than previously found
- The call structure appears to be a Gabor function - similar to that used by dolphins
- *R. aegyptiacus* may be a sophisticated echolocator after all


FIRE INSTRUCTIONS
ON DETECTING SMOKE OR A SMELL OF BURNING —
INVESTIGATE IMMEDIATELY

Appendix 3q

Dick Altes

Time/aspect varying biosonar targets: Modeling and classification

Richard Altes, Chirp Corp., La Jolla, CA, USA

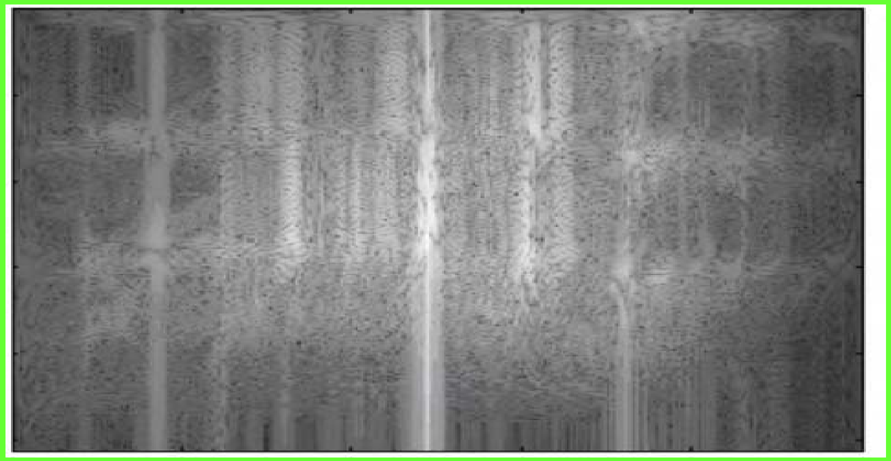
CF-FM bats and FM bats are sensitive to echo time variations caused by insect wing motion.

Dolphins (*Tursiops*) are sensitive to multi-pulse echo changes that could be caused by fish body motion and aspect variation.

These phenomena imply that animal echolocation systems are sensitive to target time/aspect variations.

Analysis of time/aspect variations can be confusing because range and time are coupled in an echo time series: An echo sample at delay τ corresponds to target characteristics at time of reflection $\tau/2$.

Spectrogram (magnitude-squared short-time Fourier transform of echo data vs. time), constructed from a sequence of echo samples



Time →

For a time varying target (including a target that changes aspect during ensonification), does the spectrogram represent time invariant target properties at a sequence of ranges or time variations within each analysis window?

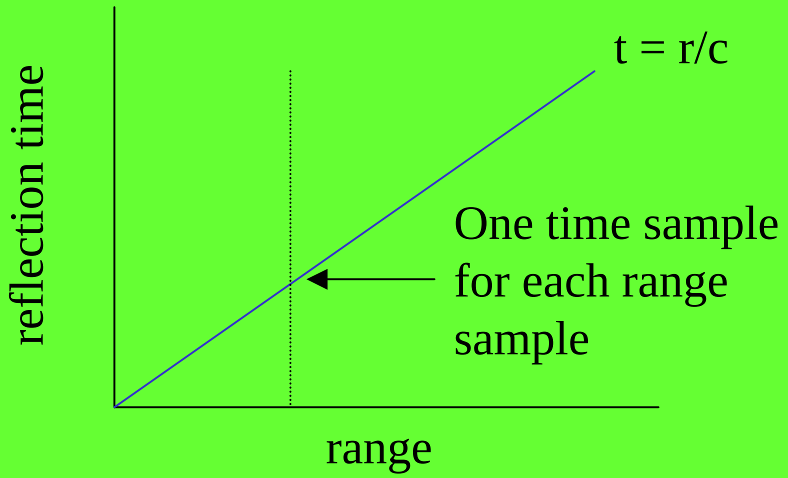
The answer is ambiguous because echo samples represent both time and range variation; the echo at delay τ corresponds to target characteristics at range $(c/2)\tau$ and at time $\tau/2$.

Range/time confusion is associated with coupling of range and time samples along a line in the range-time plane corresponding to reflection time r/c and delay 2r/c. Only one time sample is permitted at each range sample.

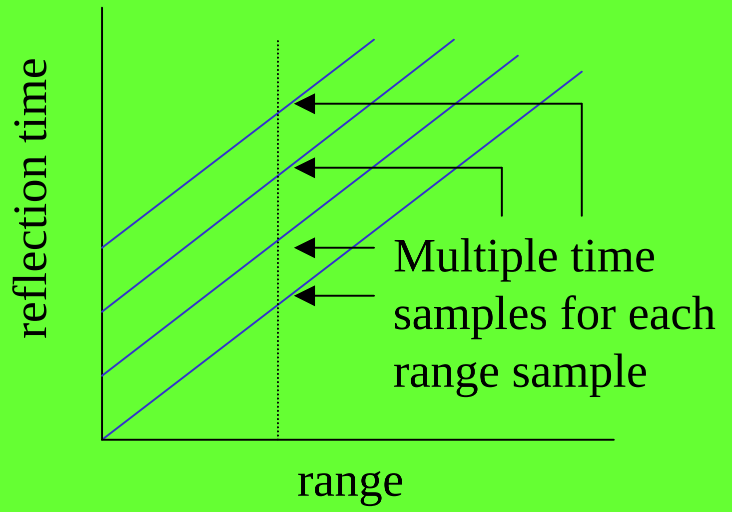
To solve this problem, transmit multiple pulses or model a long duration waveform as a sequence of short-time (sub-interval) signals with different transmission times.

Ambiguities are avoided by making the pulse repetition interval greater than the maximum expected delay difference in the echo data, by frequency coding short-time, sub-interval echo components via an FM transmission, or by filters based on target-induced Doppler shifts.

Reflection time vs range for a waveform transmitted at t=0



Reflection times vs range for a sequence of pulses or for short-time components of a long duration waveform transmitted at t1, t2, …



Surface shape modeling of time-varying targets

Represent moving/rotating surfaces by arrays of point scatterers (Huygens reflectors), where each point reflector has an individual delay and Doppler shift or Doppler induced scale factor (for a wideband signal), measured at the time of reflection (the time of transmission + r/c).

$$\hat{y}(t) = \sum_p \sigma_p x(t-\tau_p)\exp(j2\pi\phi_p t) \quad \text{(narrowband)}$$

$$\hat{y}(t) = \sum_p \sigma_p s_p^{1/2} x[s_p(t-\tau_p)] \quad \text{(wideband)}$$

$\hat{y}(t)$ = echo model,

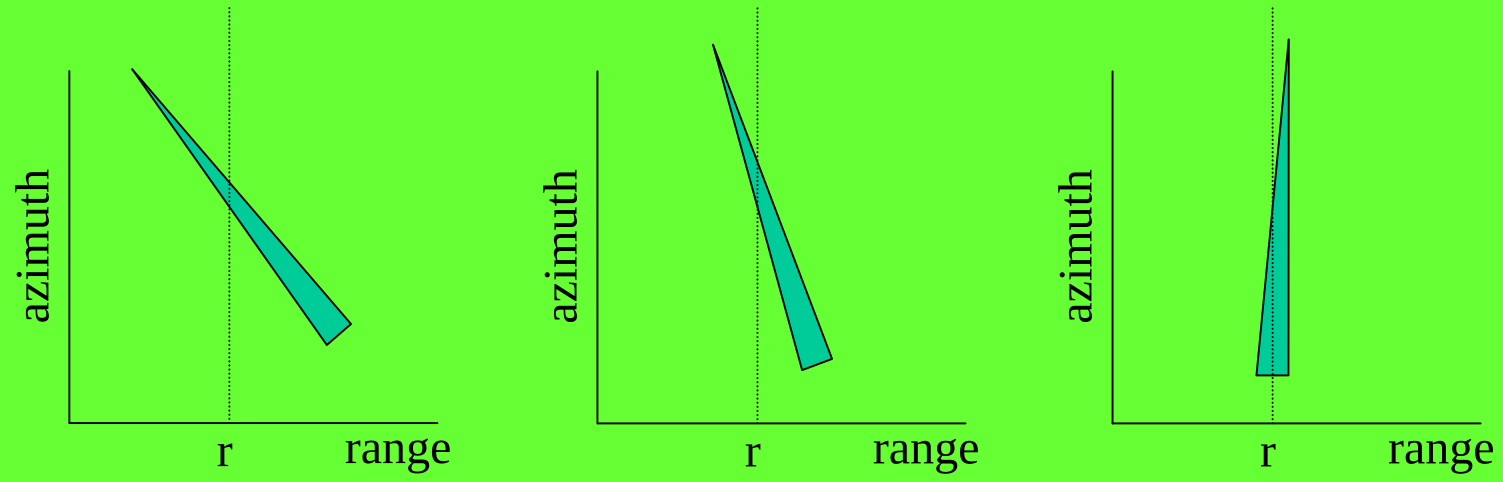
x(t) = transmitted signal,

p = an index enumerating the different point scatterers that comprise the target

Time-varying target configuration at sample time t_1+r/c

Time-varying target configuration at sample time t_2+r/c

Time-varying target configuration at sample time t_3+r/c



Shape-motion-orientation hypothesis testing using echoes from time/aspect varying targets

A receiver that tests target shape-motion-orientation hypotheses uses these variables together with the transmitted signal to produce Huygens point target echo models $\hat{y}_k(t)$ for a sequence of transmitted pulses or for sub-interval components with transmission times $t_1, \ldots, t_K$.

$$MSE_k = \int_{-\infty}^{\infty} | y_k(t) - \hat{y}_k(t) |^2 \, dt$$

where $y_k(t)$ = observed echo for the kth pulse or signal sub-interval component.

Assuming that samples of $y_k(t) - \hat{y}_k(t)$ are independent and Gaussian distributed, and that all shape-motion-orientation hypotheses are equally likely before echo data are observed, the most likely shape-motion-orientation hypothesis after observation of K echoes minimizes

$$\sum_{k=1}^{K} MSE_k .$$

The mean-square error can be approximated by the mean-square difference between the spectrograms of the data echo and the model echo, integrated over time and frequency.

For energy normalized echoes, shape-motion-orientation hypotheses can be evaluated with a spectrogram correlation operation.

Shape-motion-orientation echo models vs. synthetic aperture sonar (SAS)

SAS uses observations from multiple aspects to compensate for poor cross-range resolution and to estimate the reflectivity of each of the point scatterers in the Huygens target model.

SAS does not use target shape/orientation hypotheses, but SAS depends on an exact model of the relative motion between the transmitter/receiver and the target.

The required number of echoes, the total aspect change, and dependence on exact relative motion are all reduced with delay-and-sum semi-coherent SAS that uses a nonlinear (logarithmic) transformation of pulse-compressed echo envelope samples (BioSAS).

BioSAS errors pertain to point reflectivity (pixel) errors, not directly to errors in estimated shape and orientation parameters.

Mismatch between echo data and shape-motion-orientation echo models, however, do directly depend on errors in shape and orientation parameters.

Shape-motion-orientation echo models thus are better suited to maximum likelihood estimation of shape and orientation parameters than BioSAS processors. Shape-motion-orientation echo models should require fewer echoes for estimation of relevant parameters for shape discrimination between different time/aspect varying targets.

If shape-motion-orientation echo models require fewer echoes than BioSAS, then they are better models for dolphin and bat object discrimination, since dolphins and bats generally require fewer echoes than BioSAS for such discrimination.

Feature-based classification of time/aspect varying sonar targets

Shape-motion-orientation estimation with model-based echo synthesis may become unreliable because of clutter and multipath, insufficiently sophisticated modeling, and range ambiguities between the short-time sub-intervals of a long-duration transmitted waveform.

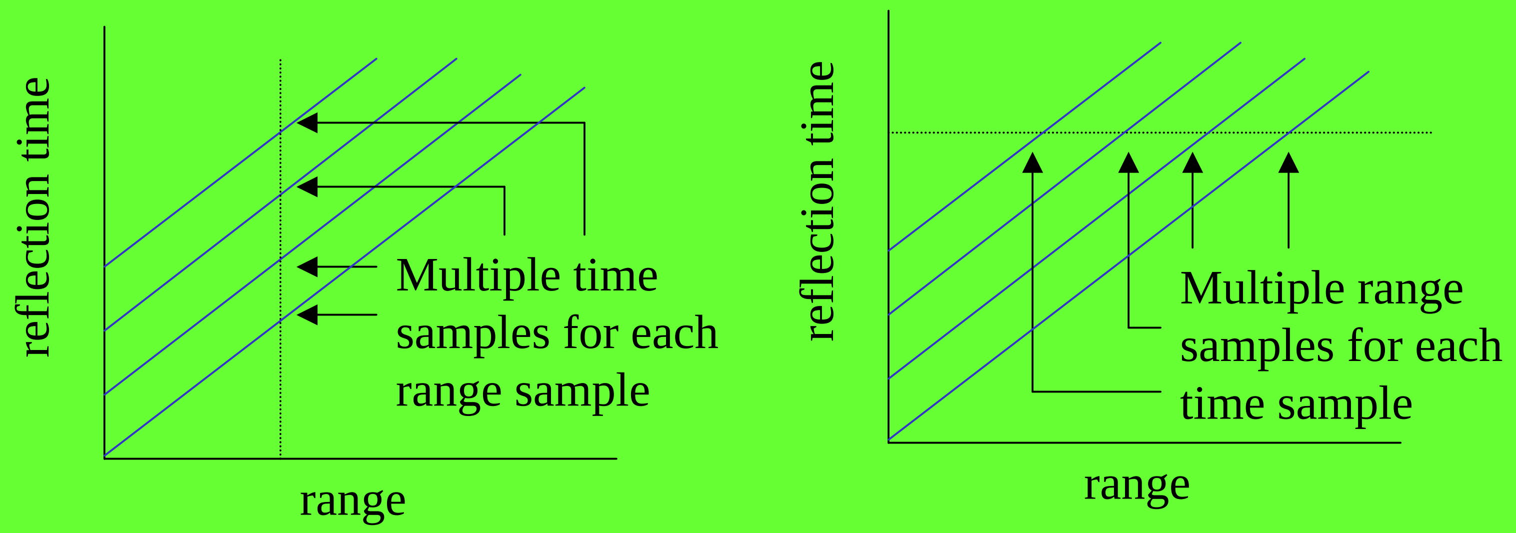
Range/time variations can be modeled by transitions between features that are extracted from short echo intervals.

Similar feature vectors (e.g., samples of similar short-time echo power spectra) can be represented by a single feature vector (vector quantization) which represents the state of the system at a given time.

Different targets have different state transition probabilities as a function of range and time. These differences can be tested with hidden Markov models (HMM) or dynamic programming (DP).

Departure from the line t = r/c in the range-time plane (via multi-pulse or sub-interval processing) increases the degrees of freedom for state transition models, and thus improves the performance of classifiers that are based on these models.

Reflection times vs range for a sequence of pulses or for short-time components of a long duration waveform transmitted at t1, t2, …



Training classifiers with large, real-world datasets and real-world experience

Vector quantization of features and state transition probabilities in HMM and DP echo classifiers depend on training data.

The technology of unmanned undersea and airborne vehicles now allows a classifier to be trained by collecting large, real-world datasets in realistic environments.

These datasets and any information that is gained from a teacher or from experience can be shared by communication between vehicles.

Receiver requirements include the discovery of new, unlabeled data classes and reconfiguration of a classifier to identify them.

Developmental psychology and bat/dolphin ecology may become important for the biologically-inspired design of adaptive acoustic sensory systems that learn to classify time-varying echo data from large, interactive training sets.

Summary

Time variation in biological sonar is caused by insect/fish body motion and/or aspect changes over a sequence of transmitted pulses.

Experiments with bats and dolphins indicate sensitivity to these changes.

Descriptions of time-varying targets include (1) echo models predicted from Huygens (point target) modeling of moving surfaces and (2) range/time transitions of echo feature vectors.

New insights include (1) the possibility of model-based estimation of surface shape, motion, and orientation parameters and discrimination between target shapes without the extended aspect observation interval required for SAS, and (2) the use of state transitions between selected points on the range-time plane (rather than along the line $t = r/c$) to improve HMM or DP echo classifiers.

Further improvements to HMM and DP classifiers are obtained with large, real-world datasets in combination with classifiers that recognize unlabeled classes and modify classifier operations to identify them.

Commercial products that can utilize these capabilities include (1) an active ultrasound halter that can be used for patient monitoring in the same way as present electrocardiogram halters, and (2) collision avoidance systems for automobiles.

Basic Science

Group 1

Appendix 3r

BASIC SCIENCE IN BIOACOUSTICS

BASIC SCIENCE

- WE NEED TO DO EVERYTHING WE HAVEN’T YET DONE!!
- IT WILL COST A LOT OF MONEY BUT WILL BE WORTH IT!!
- THE TIMELINE IS APPROXIMATELY 15 GENERATIONS

BASIC SCIENCE

- NEED TO BE SURE THE BAT AND DOLPHIN DON'T USE DIFFERENT SYSTEMS AND IF THEY DO HOW ARE THEY DIFFERENT?
  - JITTER EXPERIMENT IN DOLPHINS
    - TO EXPLORE HIGHLY NONLINEAR RELATION BETWEEN ECHO BANDWIDTH AND TEMPORAL ACCUITY
  - ASPECT INDEPENDENT RECOGNITION OF SHAPE IN BATS
  - CAN THEY DO TARGET RECOGNITION WITH A SUFFICIENTLY SMALL NUMBER OF ASPECTS THAT RECONSTRUCTION IS THE ONLY VIABLE EXPLANATION – "BIOSYNTEHTIC APERATURE SONAR" IN BOTH DOLPHINS & BATS

BASIC SCIENCE

- THERE IS A NEED TO DO ADDITIONAL FEATURE EXTRACTION EXPERIMENTS THAT WILL BE BETTER IDENTIFIED FOLLOWING THE PREVIOUS EXPERIMENTS FOCUSING CLOSELY ON HOW THE DIFFERNET FEATURES ARE MANIFESTED IN THE SPACIAL IMAGE, IF THEY EVEN HAVE AN IMAGE.
- PURSUE THE CROSS MODAL APPROACH TO IDENTIFY THE IMAGE TYPE, i.e. VISUAL OR ACOUSTIC.

BASIC SCIENCE

- ADAPTIVE SONAR
  - MEASURE INTEGRATION TIME AS FUNCTION OF SIGNAL LEVEL AND SIGNAL TO NOISE – BECAUSE COCHLEAR TRANSDUCERS CHANGE GAIN AND CUE IN TANDEM AS A FUNCTION OF SIGNAL TO NOISE AND LEVEL
    - WHAT CORRELATED CHANGES OCCUR IN THE BROADCAST?

BASIC SCIENCE

- OTHER RECOMMENDATIONS:
  - OPEN SHARING OF DATA SETS
  - REGUALAR MEETINGS OF THIS GROUP WITH SELECTED ADDITIONAL MEMBERS AS APPROPRIATE
    - KEEP ATTENDEE NUMBERS TO APPROX. 30

THE BASIC SCIENCE TEAM

THE CHAIRMAN

THE REPORTER

THE REALLY SMART GUYS

Defining An Effective Research Agenda:

Information Processing

Group 3 : John Fay, Leader

Participants: Les Atlas (Reporter), Devaud, Kirsteins, Andrea Trucco, Chris Clarke, Laurie Linnett

Appendix 3s

Current Situation

- Can’t replicate animals
- Limited resolution
- Modeling improvements needed
- Some understanding of physiology
- Performance bounds unknown
  - Cramer-Rao
  - Ziu Zakai
  - Barankin
  - MDL
- Animals use distinctly different processing implementation
  - Conventional processing usually assumes time-invariant systems.

Where Do We Want to Go: A?

- Implement or understand scientific results
- Equivalent performance to trained animals
  - Performance metrics
  - In detecting, classifying, and localizing man-made objects.
  - Identifying threats
  - Mapping bottom
  - Pipeline route mapping
  - Collective intelligence
- New signal representations

Where Do We Want to Go: B?

- Adaptability
  - Environmental
  - Waveform and/or processing
- Modeling and simulation
- Comparisons to conventional systems
  - Standard data set
  - Advantages (value-added)
  - Distinctiveness between conventional and bioacoustic

How do we get from Current Situation to where we want to Go?

- Identification and Classification Test set example
  - Different materials
  - Tank test
  - Open water, e.g. previous run test by Pat Moore et al
  - Establish standard data set
  - Examine new methods that achieve capabilities
  - Distribute data set to other researchers
  - Submit results to refereed journals.
- Follow-up workshops

To be Decided

- ***Schedule***
- ***Participants***
- ***Funding Level***
- ***Possible Funding Sources***
  - ONR
  - AFOSR
  - DoD MURI
  - NAVSEA, or other codes
  - European Commission
  - NATO
  - UNITA

Potential Bio Acoustic Applications

Group 4

Appendix 3t

Common Advantages of Bioacoustics

- Higher resolutions
- Higher bandwidths
- Improved ranges
- Low power

Common Bio-Acoustic Challenges and Needs

- Improved resolution (spatial, contrast)
- Reduction in number of poor images (beam distortion)
- User-friendly machine
- Reduced operator dependence of results (smart machines?)
- Wider bandwidth transducers
- Higher frequency transducers
- Improved knowledge of material properties

Environmental Applications

- Higher resolution 3D imaging of bodies
- High resolution physical modelling of 3D bodies
- High resolution 4D modelling
- Enormous range of applications at many scales

Military Applications of Bioacoustics

- Communications
- Object avoidance
- Area surveying:
  - Bathymetry
  - Mine countermeasures (MCM)
  - Sub-bottom
  - Land (traffic-ability)
- Object Detection, classification and Identification

Medical Bio-Acoustics Applications

- Tissue characterisation (needle biopsy)
- Image through bone
- Quantitative perfusion with contrast agents
- Targeted contrast agents
- Real-time 3D imaging
- True 3D blood flow imaging

Common Research Needs

•Research Operational Value for each Sub-Application for Bio-Acoustic technology;

•Signal processing and wideband transducers

•Convincing sponsors of operational value of technology to resource technology development;

•Develop "Proof of Concept Studies" for specific Applications and Techniques;

•Identification of Component development for specific applications;

•System's Engineering for New Development or Insertion to existing equipment

Potential Bio Acoustic Applications

Group 4

Appendix 3t

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- High resolution physical modelling of 3D bodies
- High resolution 4D modelling
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Biodynamics & Cognition

Robert Allen

Institute of Sound & Vibration Research
University of Southampton

Bioacoustics Workshop
4-5 May 2004

INSTITUTE OF SOUND AND VIBRATION RESEARCH

ISVR

Founded 1963

2001 Research Assessment Exercise: rated 5*

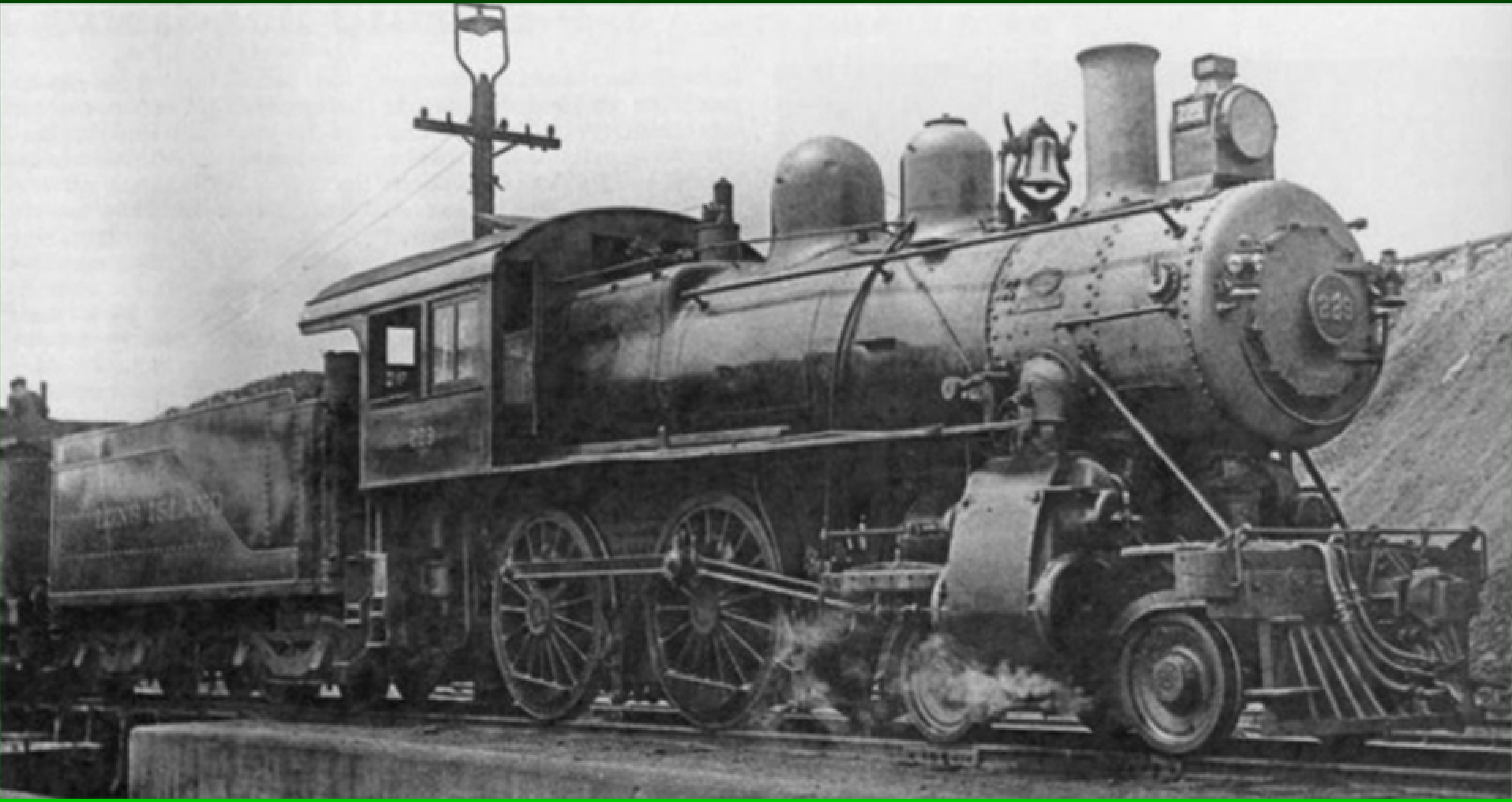
1997 Quality of Education Assessment: rated 23/24

Large Anechoic Chamber

Large Reverberation Chamber

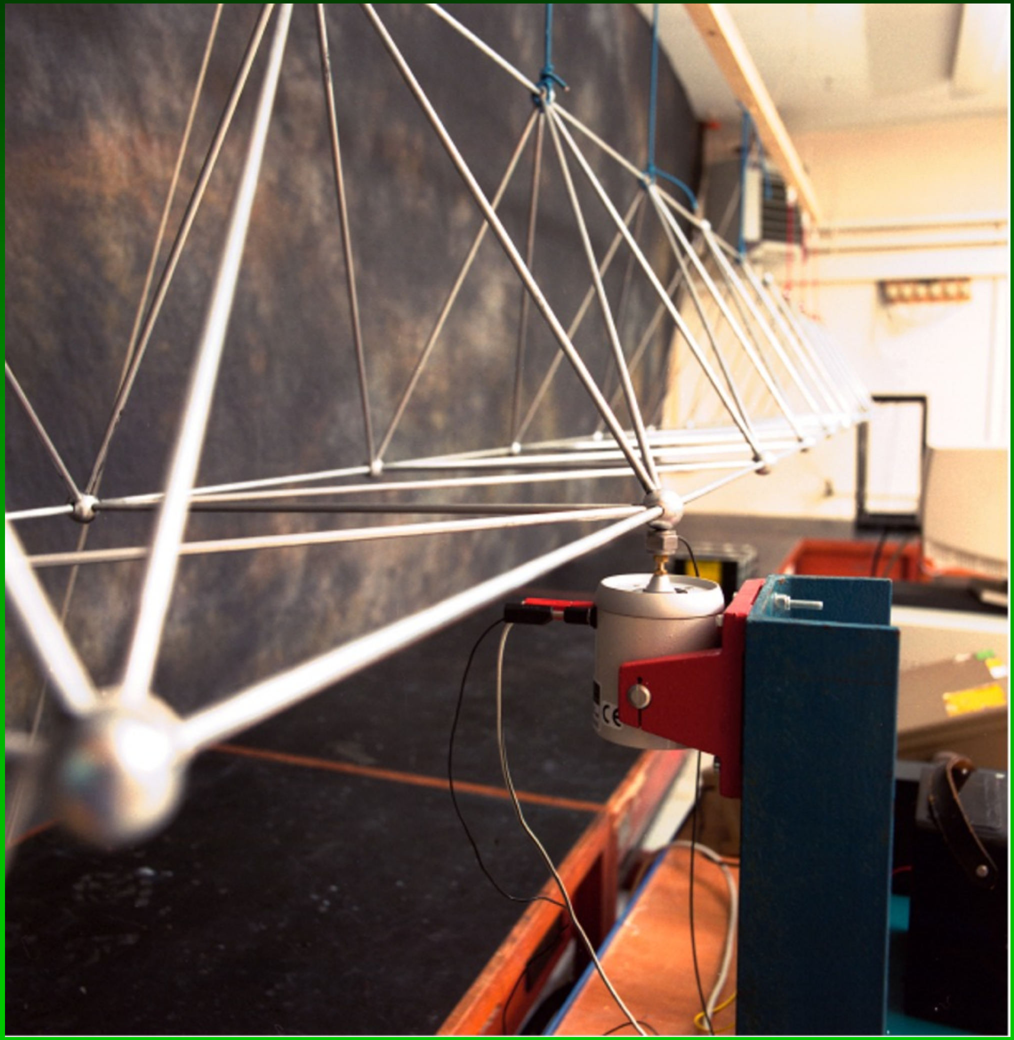
Small Anechoic Chamber

Railway Noise and Vibration



Automotive Noise and Vibration

Smart Structures



A B Wood Underwater Acoustics Laboratory

A 10 ft wave breaks over a bubble detector, which can be seen as a small black circle strapped between the cross-bars on the scaffolding.

Acoustics of ocean bed sediments

Telecommunication cables, geological surveying . . . . . .

Human Response to Vibration

SOECIC

South of England Cochlear Implant Centre

Audiology Clinic

EPSRC IMPROVES Project

- Three-year £600K Programme.
- Commenced 2001, and involves:
  - University of Southampton
  - University of Wales College Newport (UWCN)
  - University of Plymouth
  - Seaeye Marine Ltd., Fareham

AIM

- To improve the dynamic performance of advanced, multi-mission ROVs through design of new, robust, predictive control and on-line fault detection and handling subsystems

EPSRC IMPROVES Project

- Specific (lead) responsibilities:
  - Newport: Fault detection and accommodation
  - Plymouth: Intelligent control algorithms
  - Southampton: Robust control algorithms

- All three Universities are undertaking system modelling and identification studies, which uses data captured from tank tests.
- All designs to be tested and evaluated on real ROVs.

EPSRC IMPROVES ROVs

Falcon

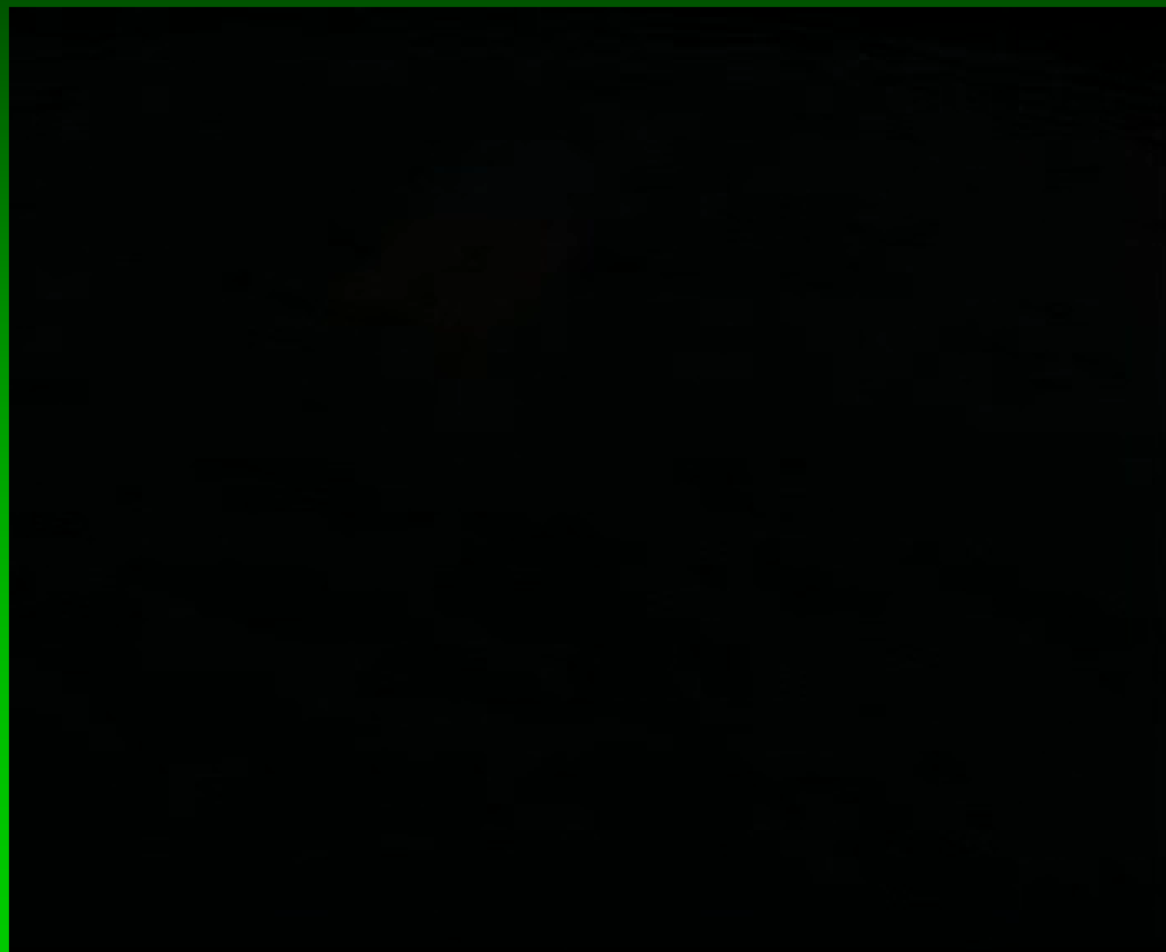
Seaeye Marine Ltd.

New vehicle in 2002

1.0mx0.6mx0.5m

Circa 50 Kg

Depth 300m max



EPSRC IMPROVES ROVs

Subzero III

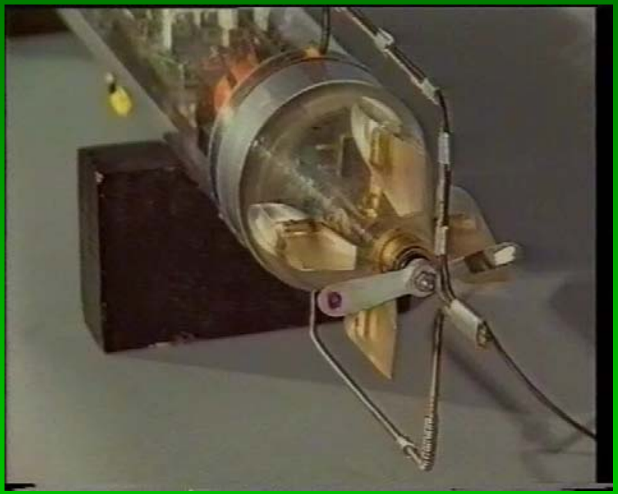
Southampton University

Length 1.0m

Max speed 4 kts

Vehicle description

- Hull (torpedo-shaped)
  1) Made of perspex with the thickness of 5mm
  2) Semi-sphere nose+cylinder body+conical tail
  3) Length: 1m, body diameter: 10cm
  4) Slightly positive buoyancy



- Vehicle manoeuvrability
  1) Propeller → forward speed
  2) Two rudders (linked together)
  3) Two stern-planes → depth

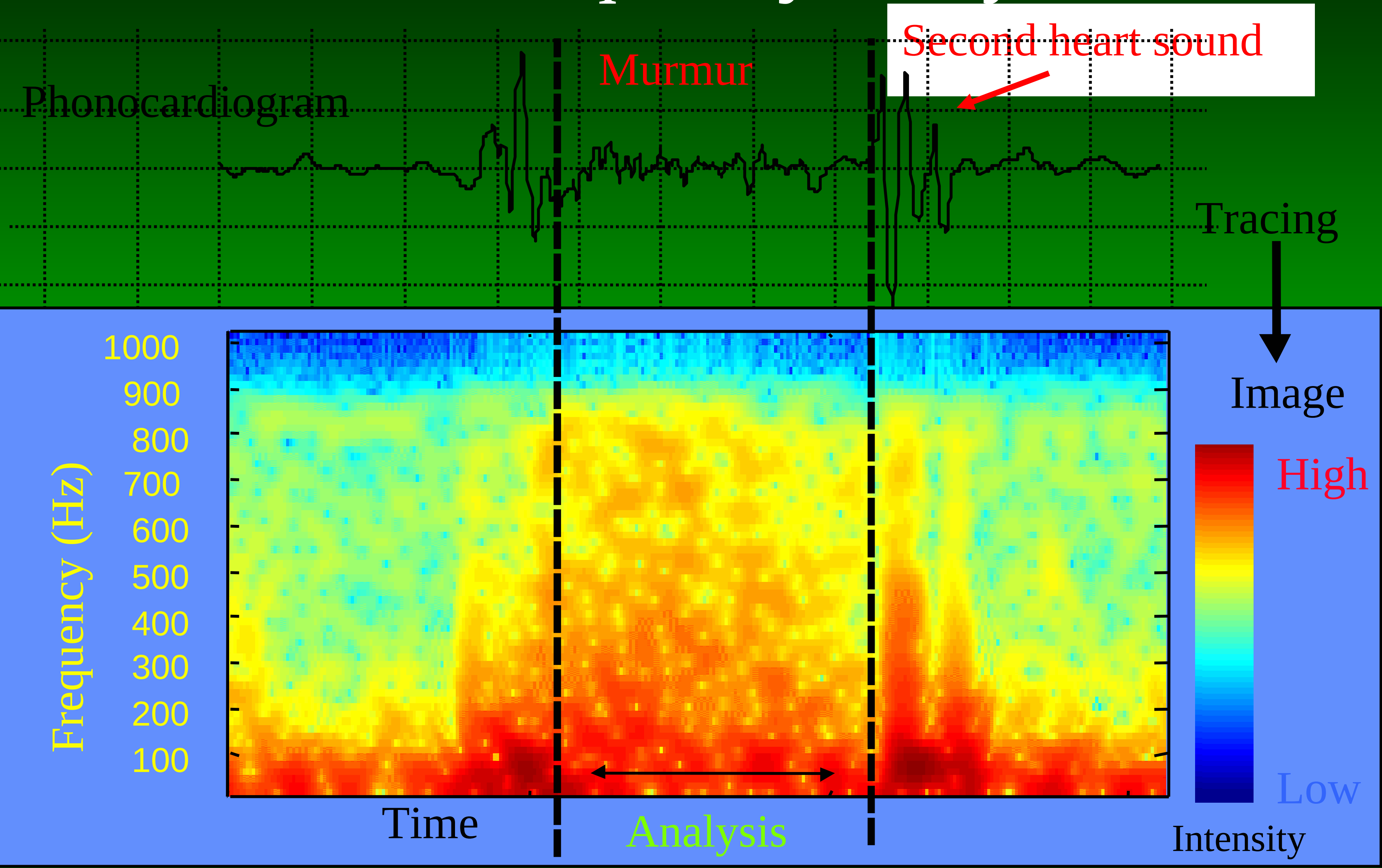
- Vehicle actuators
  1) DC motor (PWM driven) → propeller
  2) Three servomotors (PWM driven) → control fins

Biomedical Signal Processing

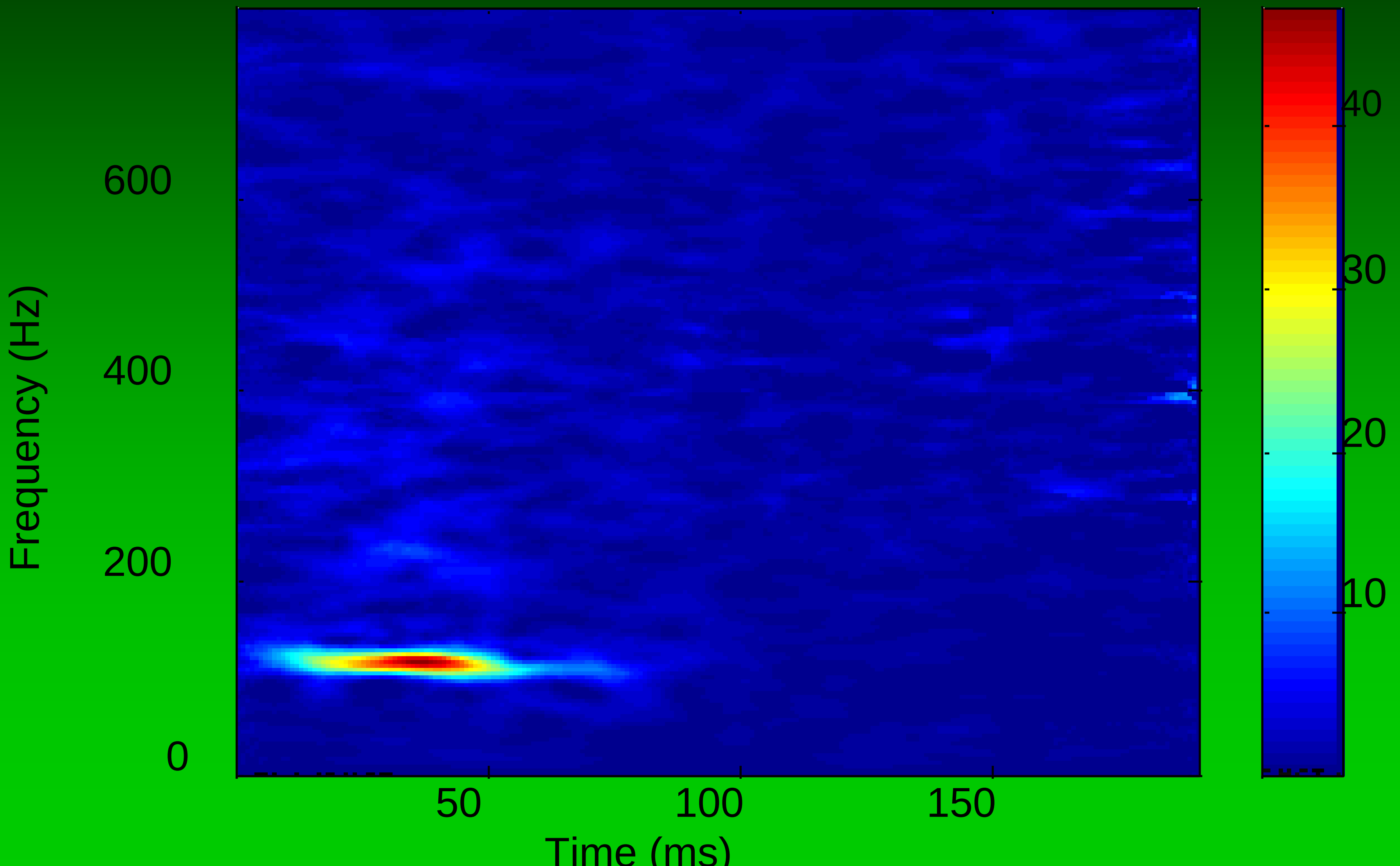
Heart sound research

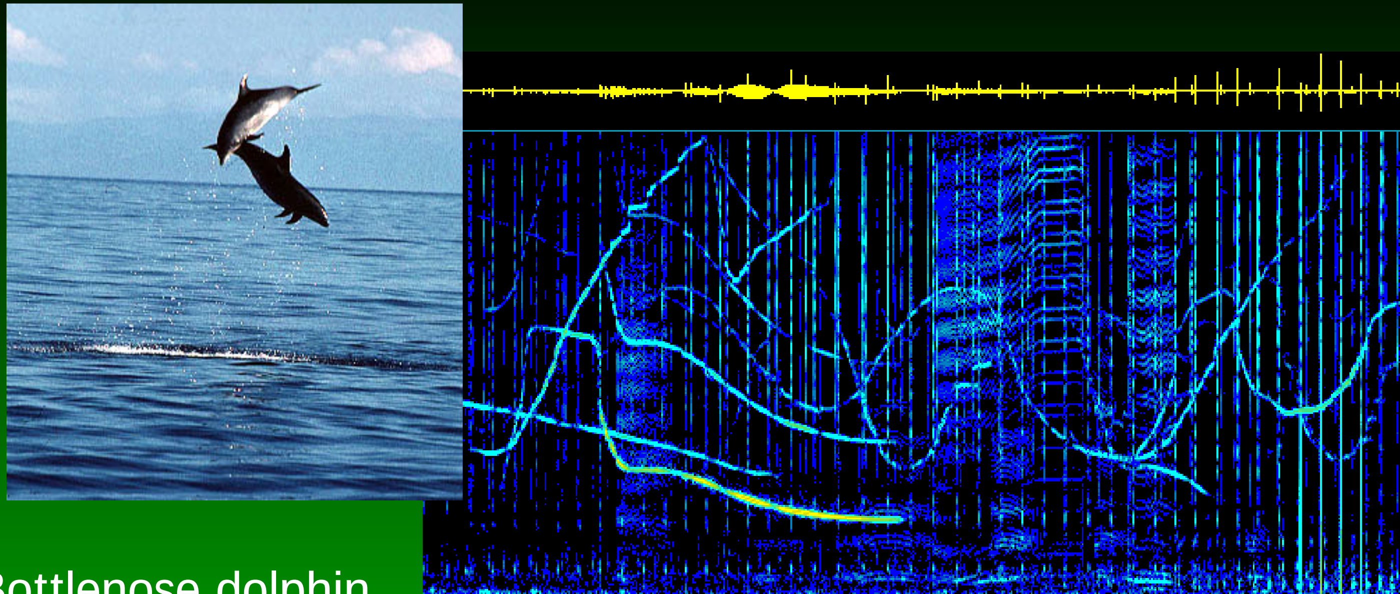
- Objective: computerised diagnosis
- Two aspects :
  - heart murmurs
  - 2nd heart sounds
- Techniques:
  - digital filtering
  - time-frequency methods,
  - signal decomposition,
  - statistical analysis

Time-frequency analysis

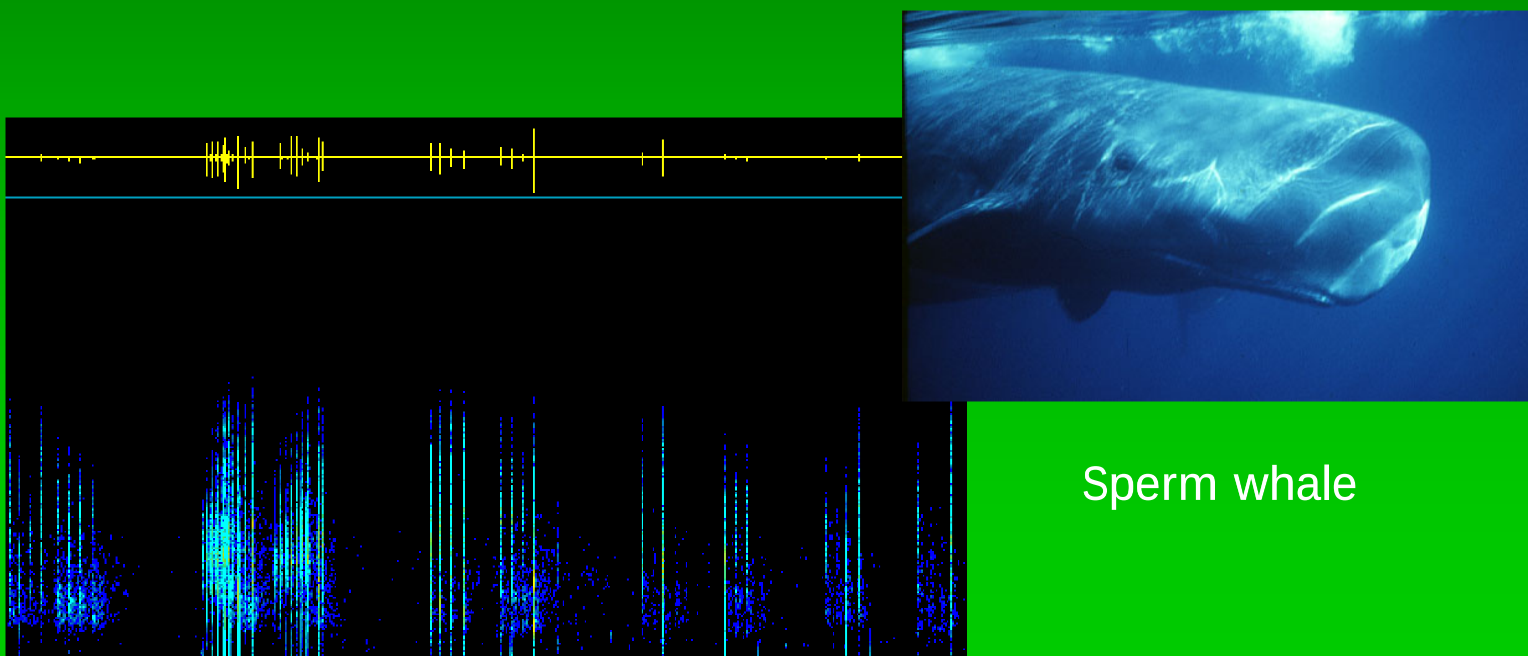


Time-frequency representation of an innocent murmur

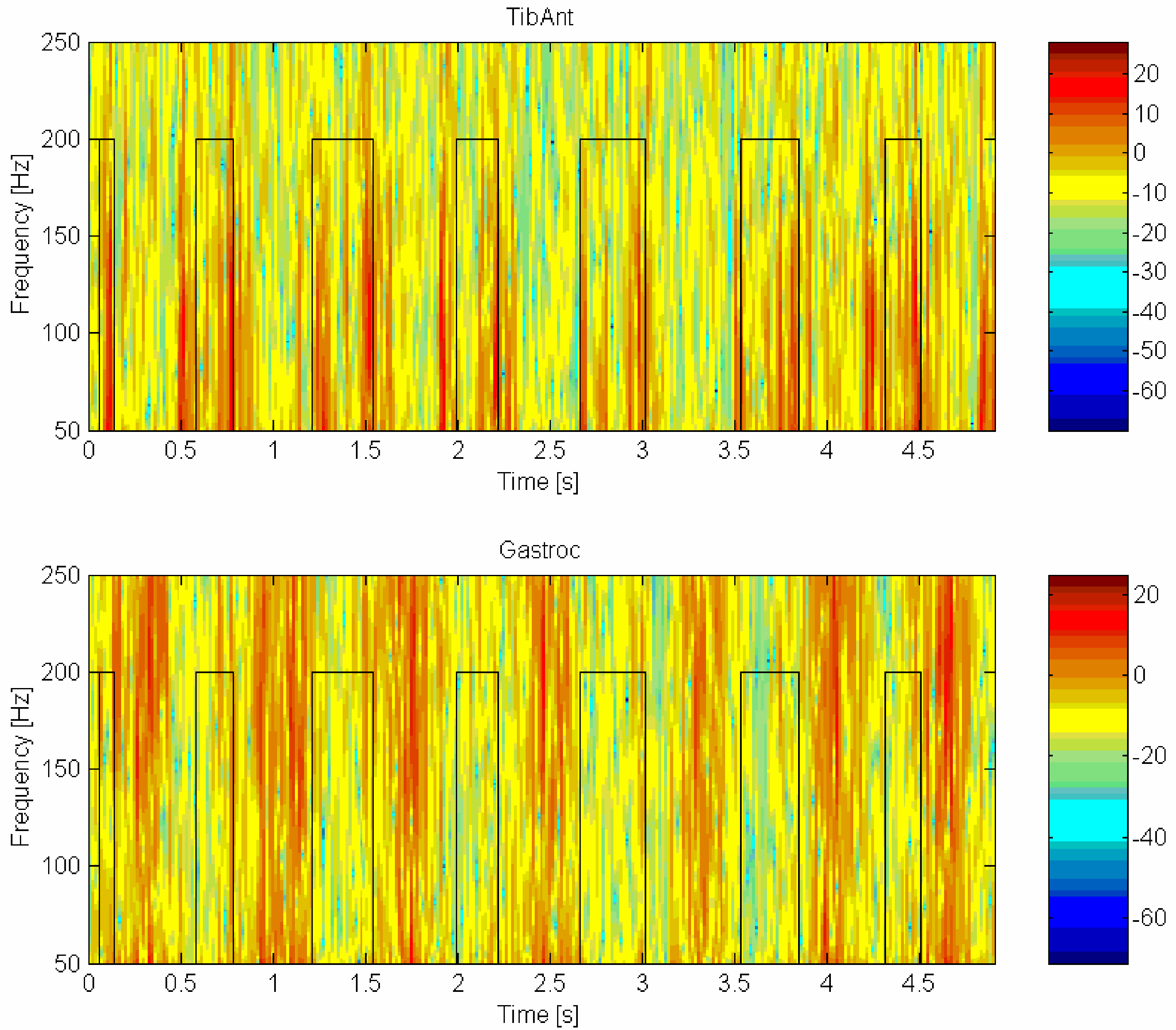




Bottlenose dolphin



Sperm whale



TibAnt
250
200
150
100
50
Frequency [Hz]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time [s]
20
10
0
-10
-20
-30
-40
-50
-60
Gastroc
250
200
150
100
50
Frequency [Hz]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time [s]
20
0
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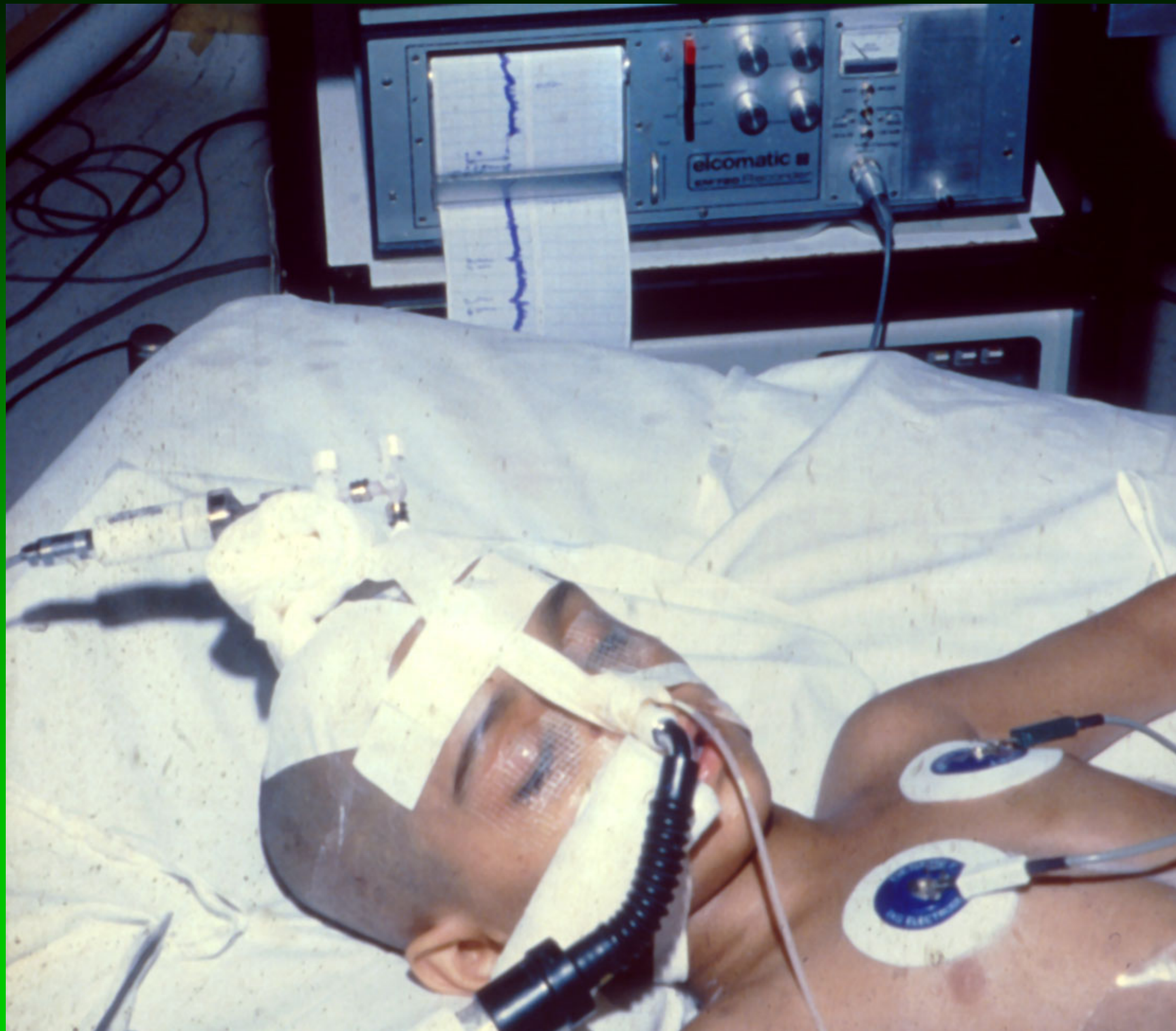
-40
-60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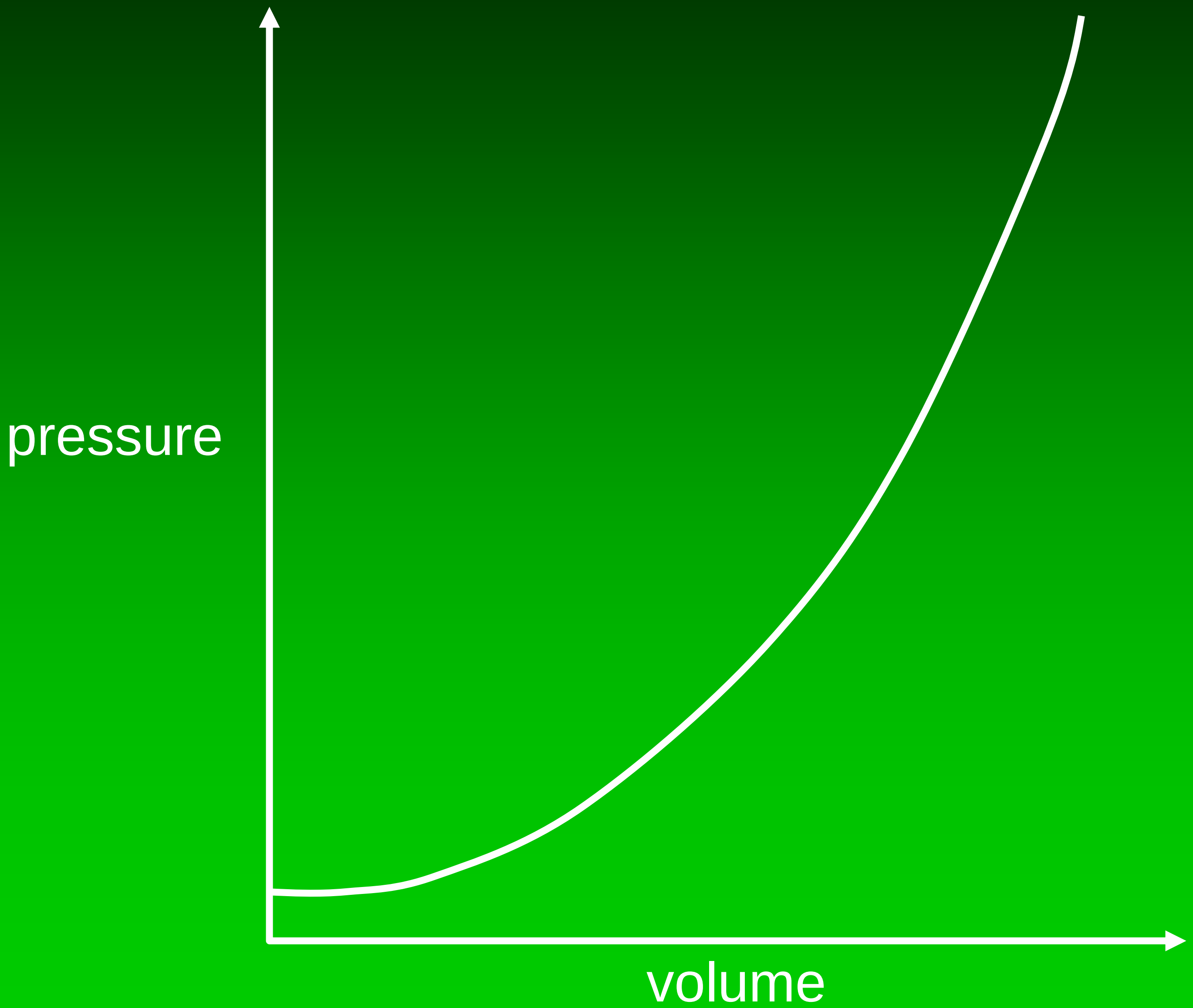
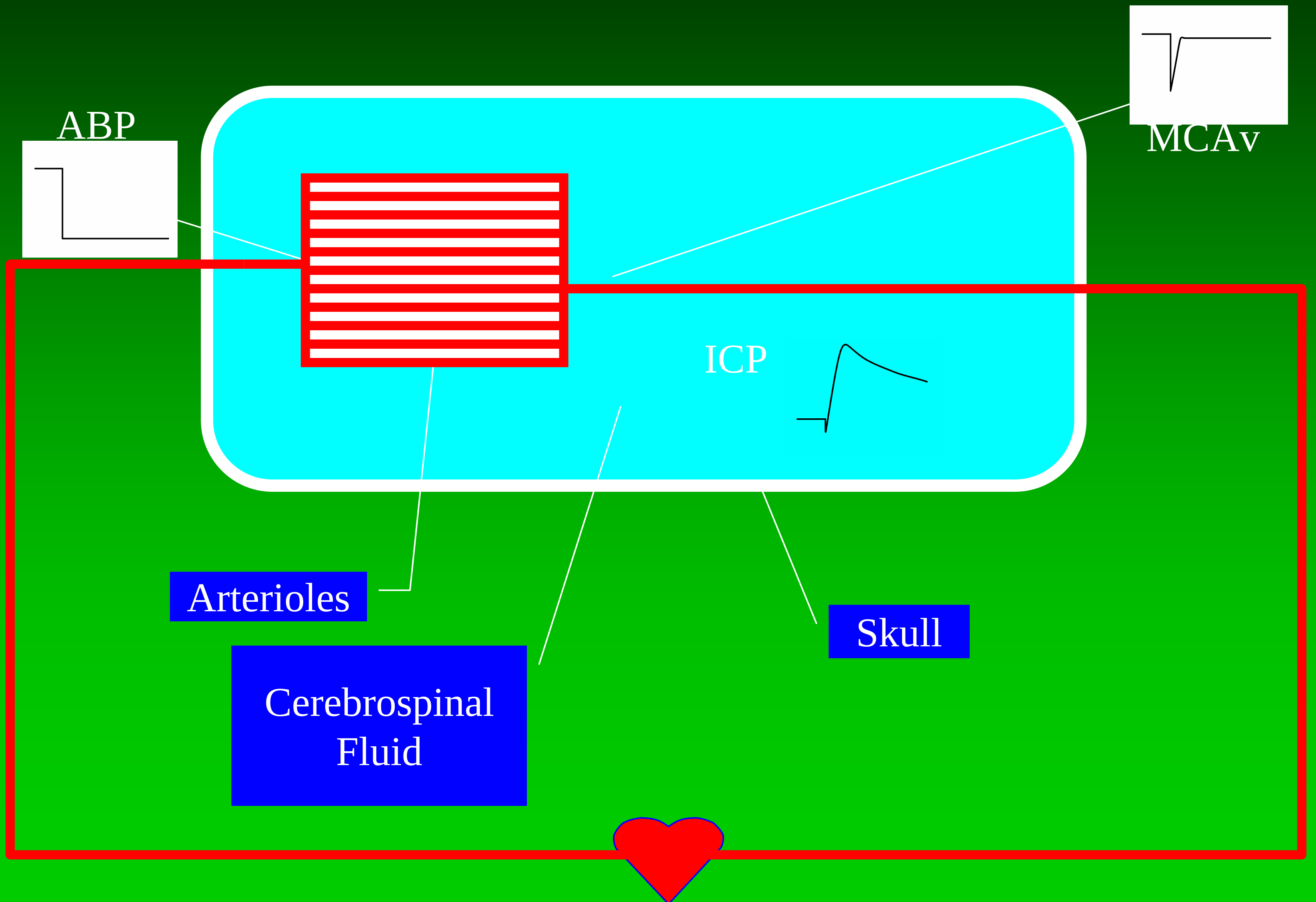
P-V Relationship



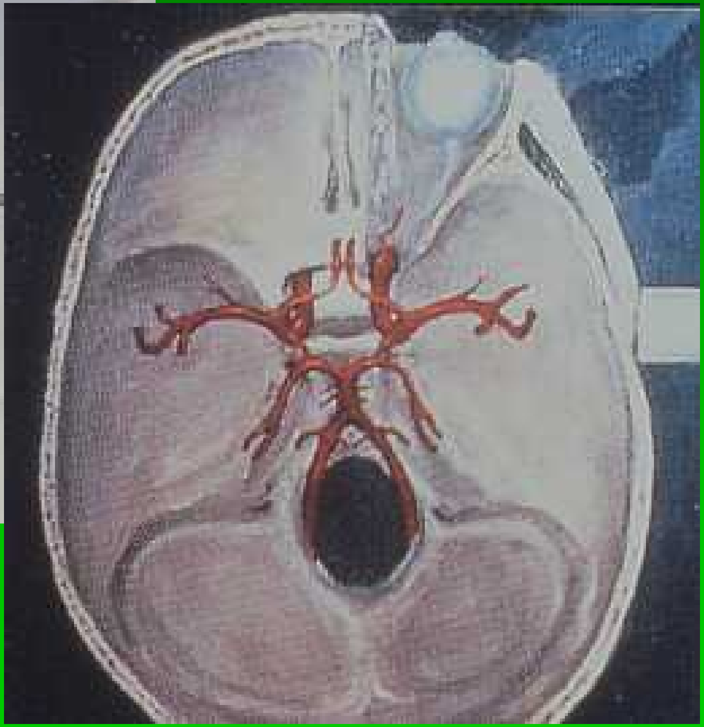
What is Cerebral Autoregulation



Aim

- The early diagnosis of possible cerebral ischaemia or secondary brain damage due to lack of cerebral autoregulation
- Use only non-invasive data to investigate the status of cerebral autoregulation

Transcranial Doppler Ultrasound



Non-invasive Measurements

- Arterial Blood Pressure (ABP) using photoplethysmography
- Middle Cerebral Artery Blood Flow velocity (MCAv) using Transcranial Doppler Ultrasound
- End-tidal CO_2 (pCO_2) using capnography
- Others, e.g. PO_2

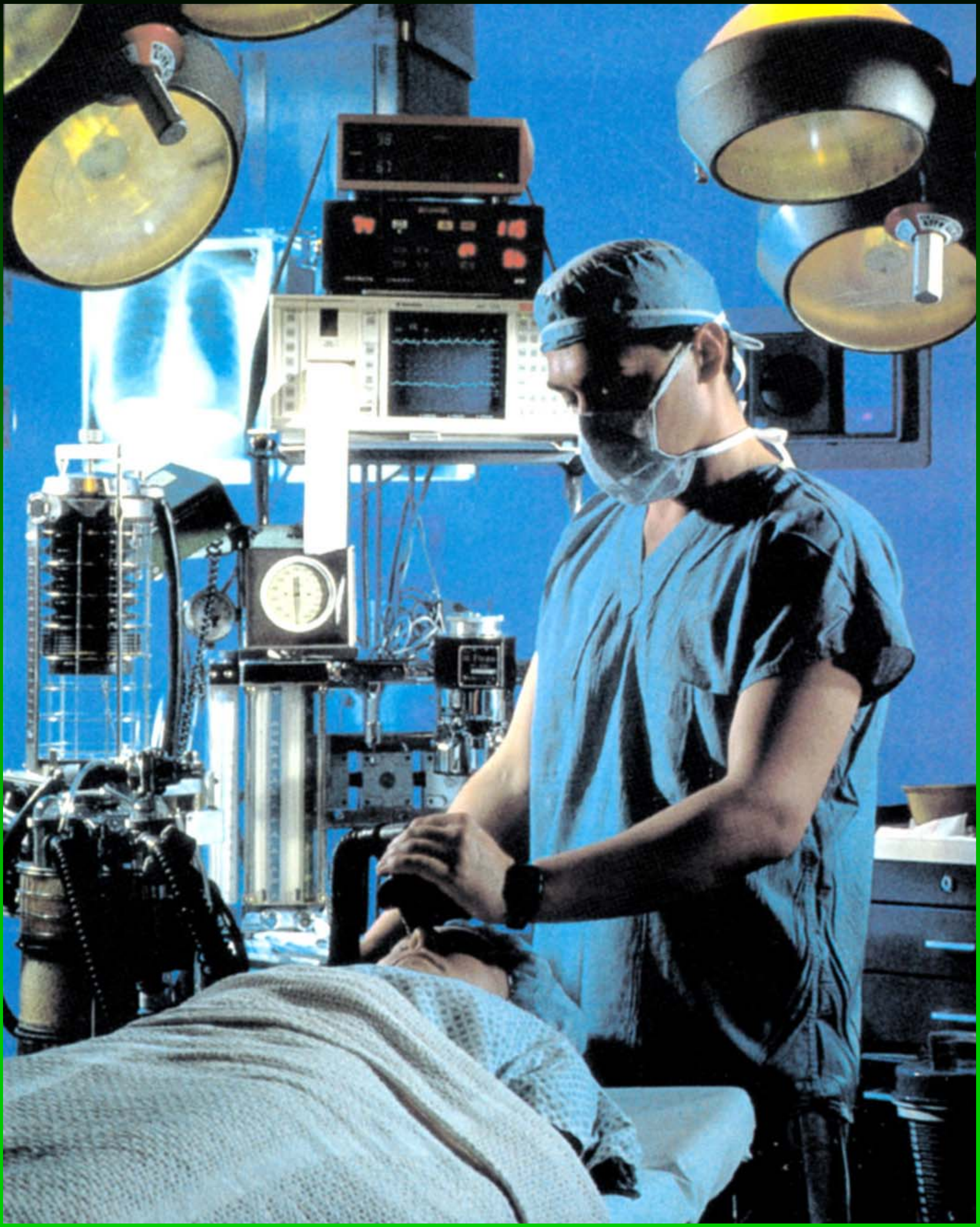
Two ABP stimulating techniques

Thigh Cuff

(Negative step-like)

Lower Body Negative Pressure (LBNP)

(Sinusoidal)

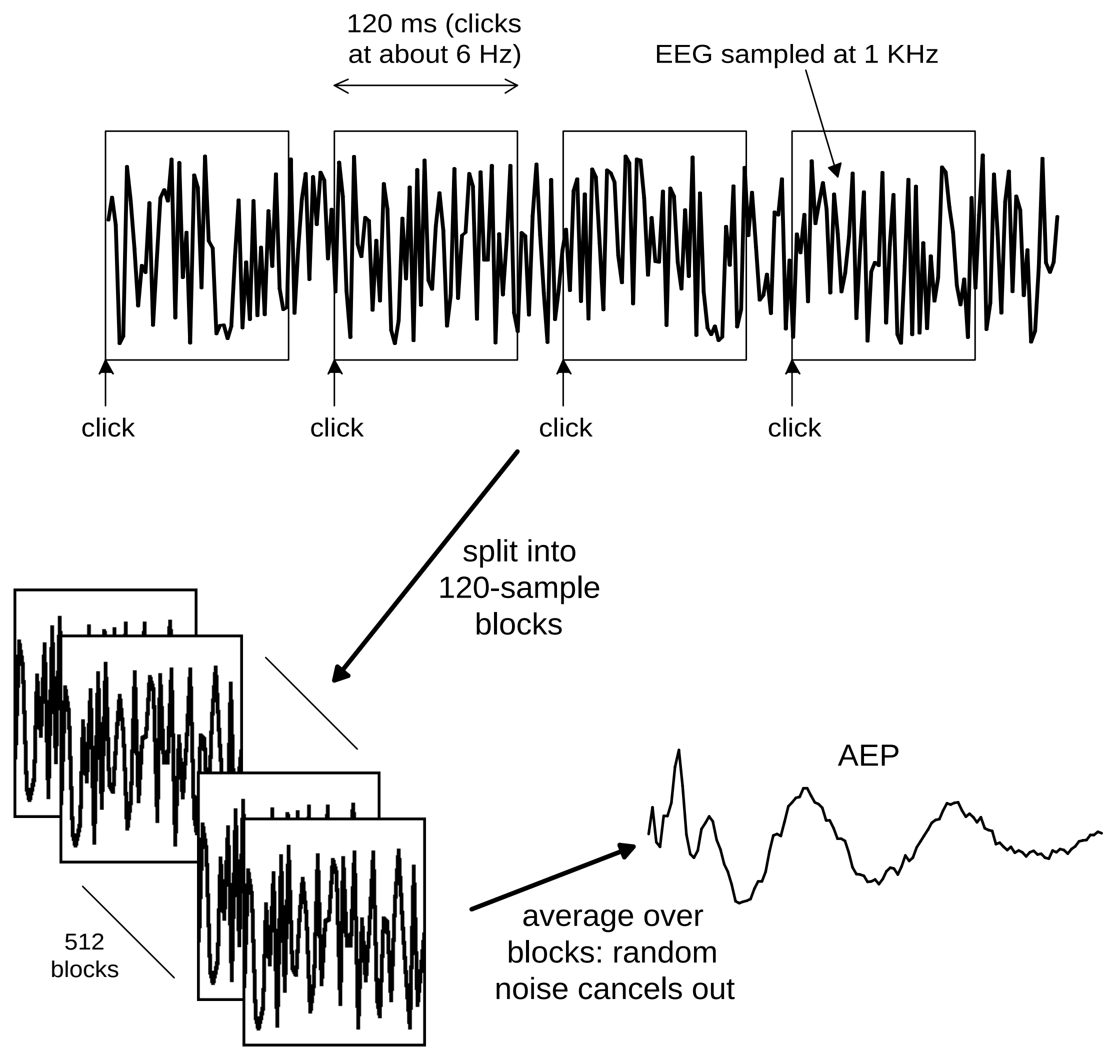


Reasons to measure anaesthetic depth

- Must ensure that patients adequately anaesthetised

- Patients can also be anaesthetised too deeply

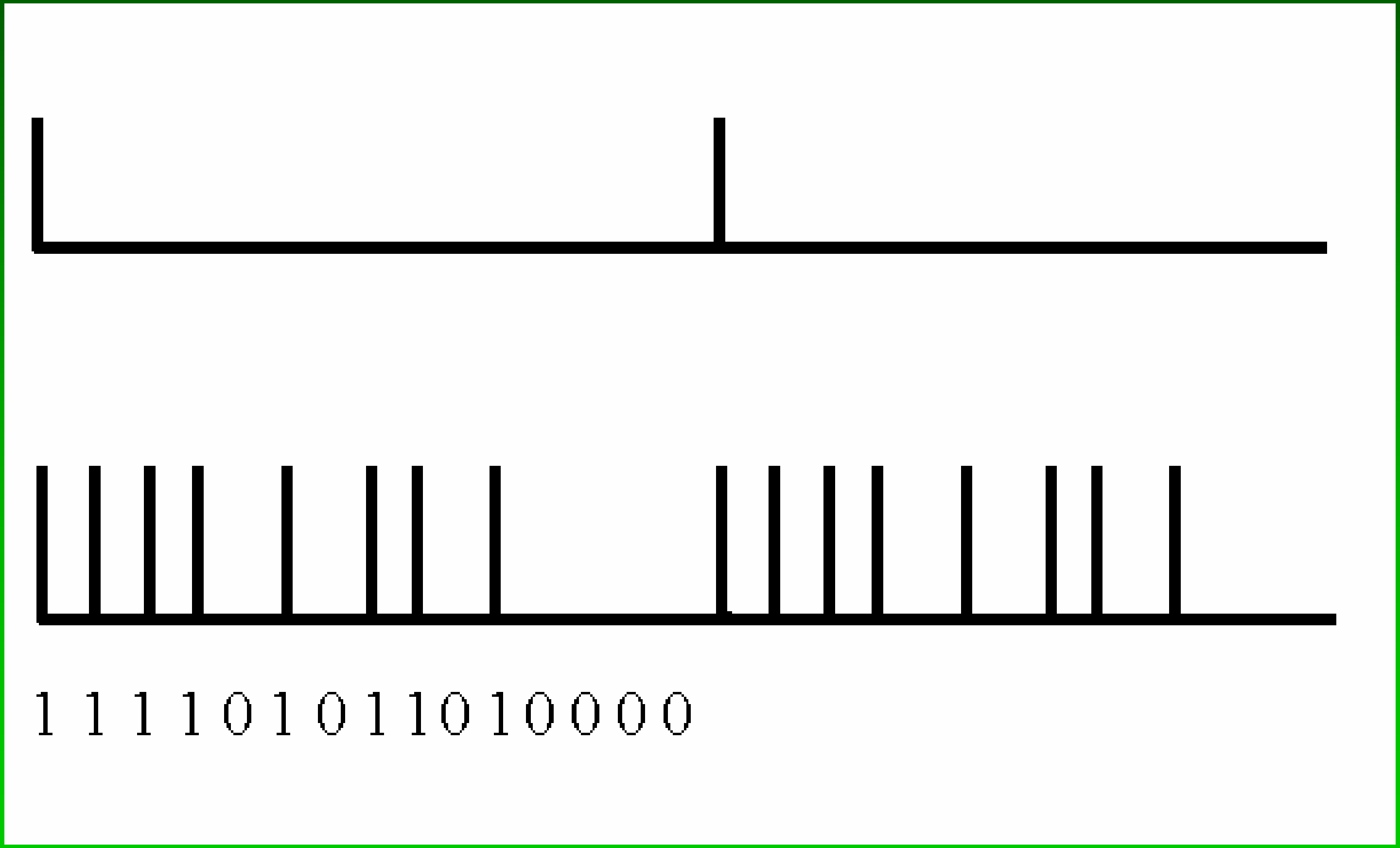
- Anaesthetic ‘cocktail’ + muscle relaxants

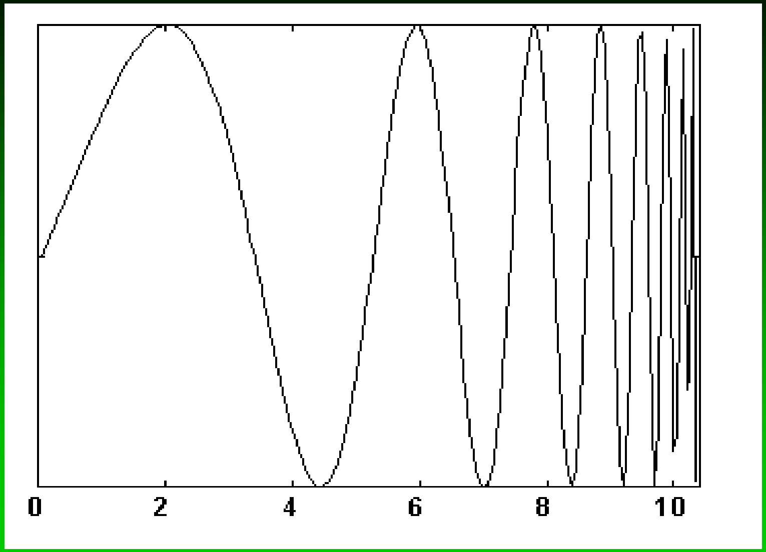

120 ms (clicks
at about 6 Hz)
EEG sampled at 1 KHz
click
click
click
click
split into
120-sample
blocks
512
blocks
AEP
average over
blocks: random
noise cancels out

Techniques which may speed up the measurement

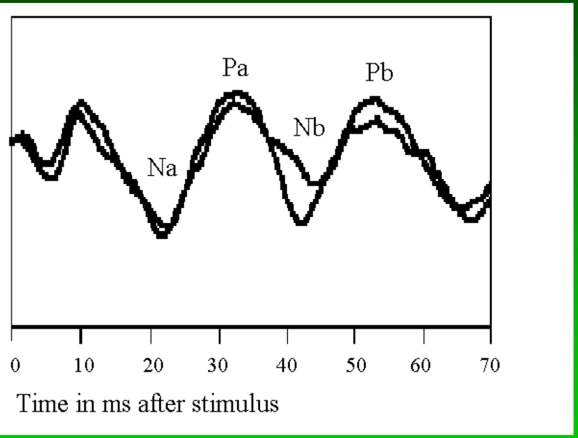
- Increase the conventional click rate
- Use Maximum length sequences (Pseudo-random binary sequences)
- Use chirps which account for frequency dispersion on the basilar membrane
- Use adaptive filtering and other signal processing techniques

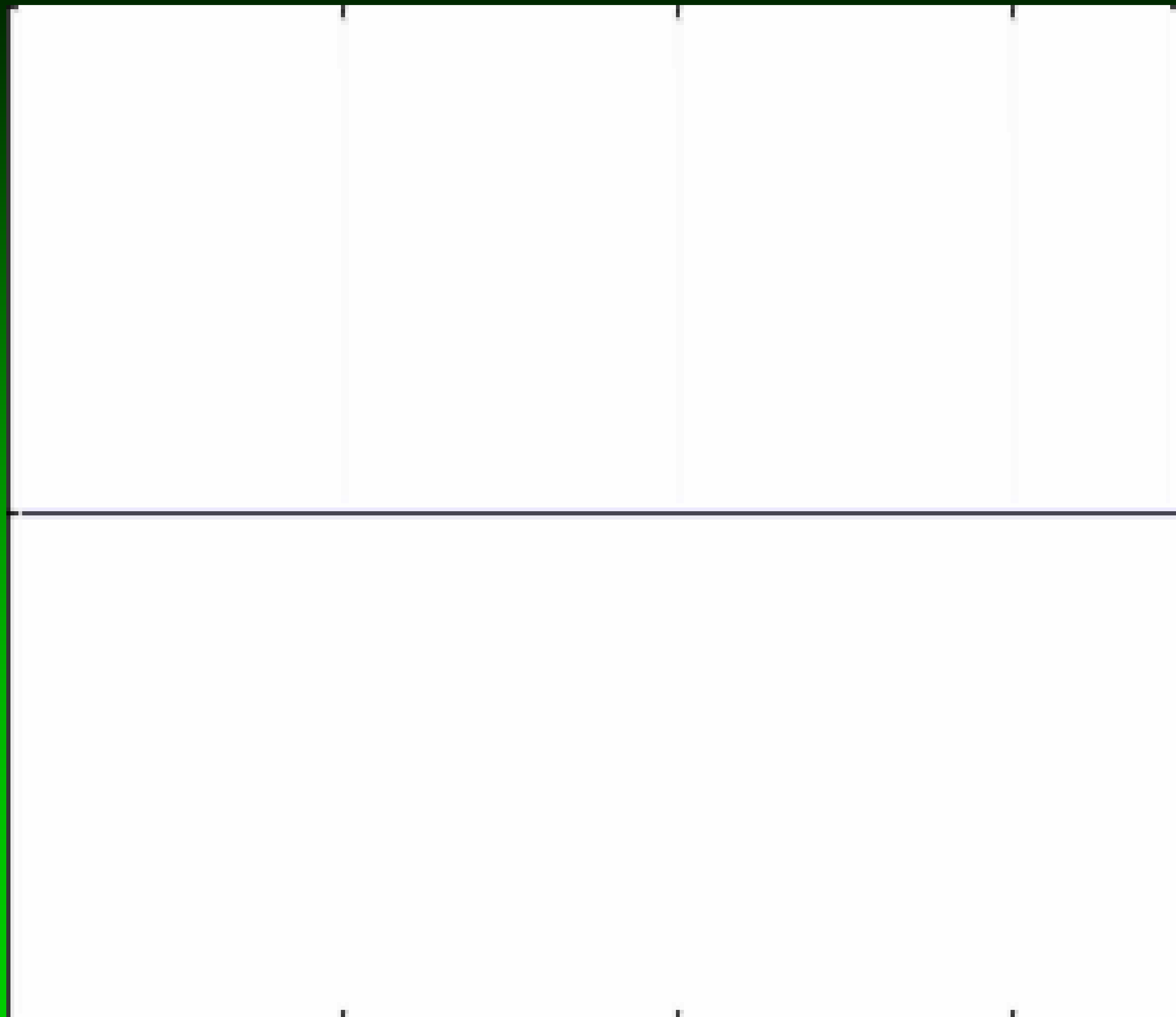
Conventional clicks vs a MLS sequence

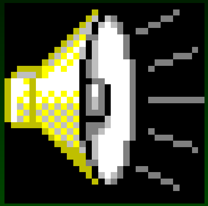




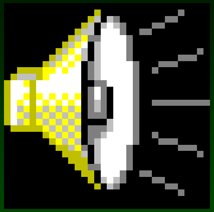
A typical Middle-Latency Response



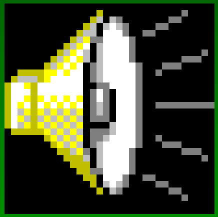




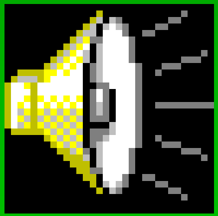
Clicks: 5 /sec



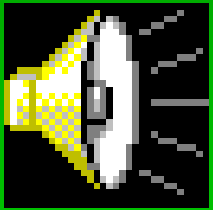
Clicks: 15 /sec



Clicks: MLS

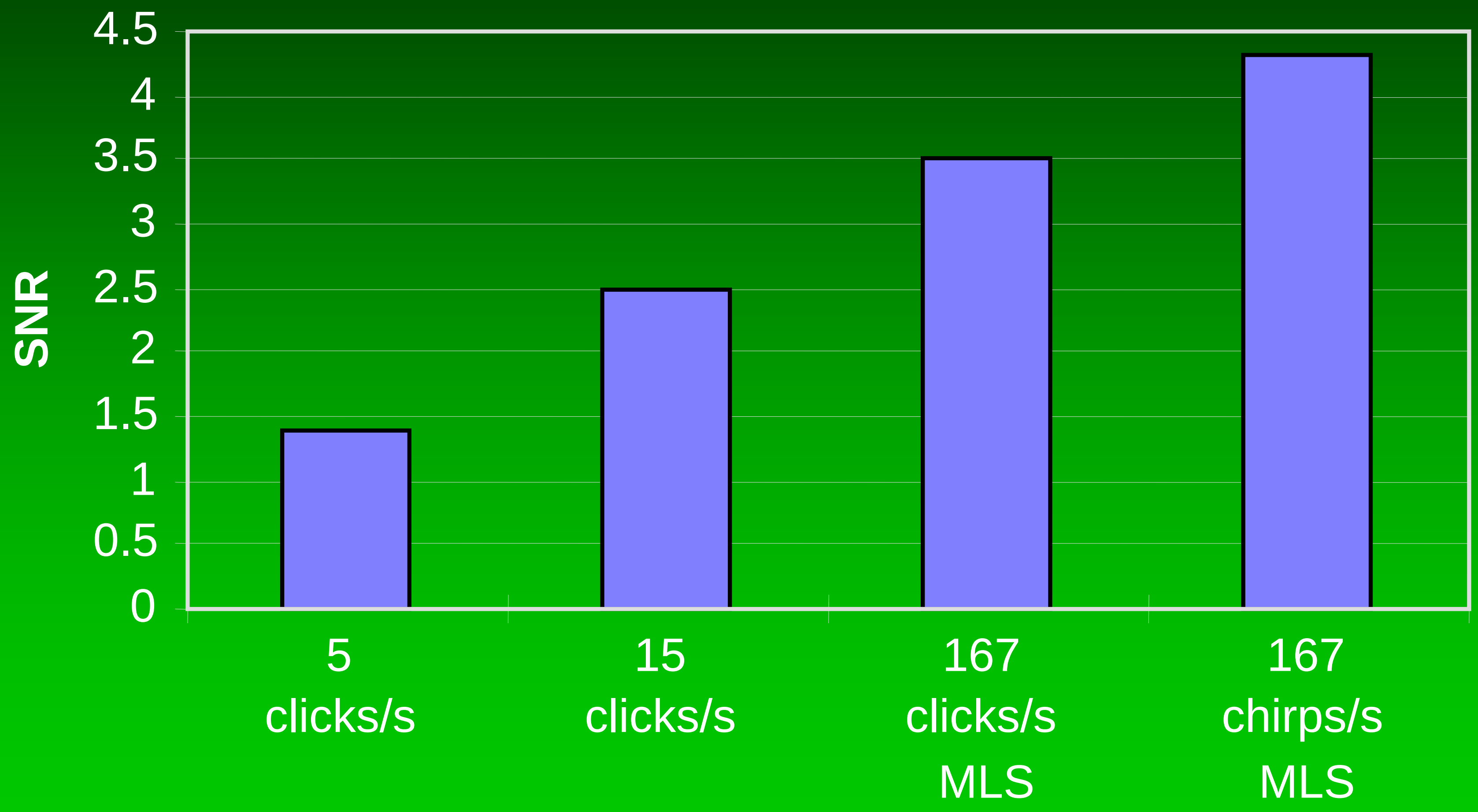


Chirps



Chirps: MLS

Variation in SNR with stimulus



Variation in Test Speed with Stimulus
(relative to 5 clicks/s)