An SNR Maximization Behaviour for Autonomous AUV Control

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Background

- AUVs are becoming a sensing platform of increasing interest for conducting ASW
    - Low cost
    - Mobility
    - Able to be inserted in high risk environments
- When operated underwater , AUVs have limited ability to communicate with other assets within the ASW network
    - Acoustic communications are low bandwidth and limited range
- AUVs therefore must have the ability to react to their sensors in an at least semi-autonomous way, making local decisions based on assumptions about the target and collaborating assets
- In this talk we propose a model based control algorithm for AUVs bistatically receiving reverberation and target returns to try to maximize the SNR

Maximize SNR Technical Approach

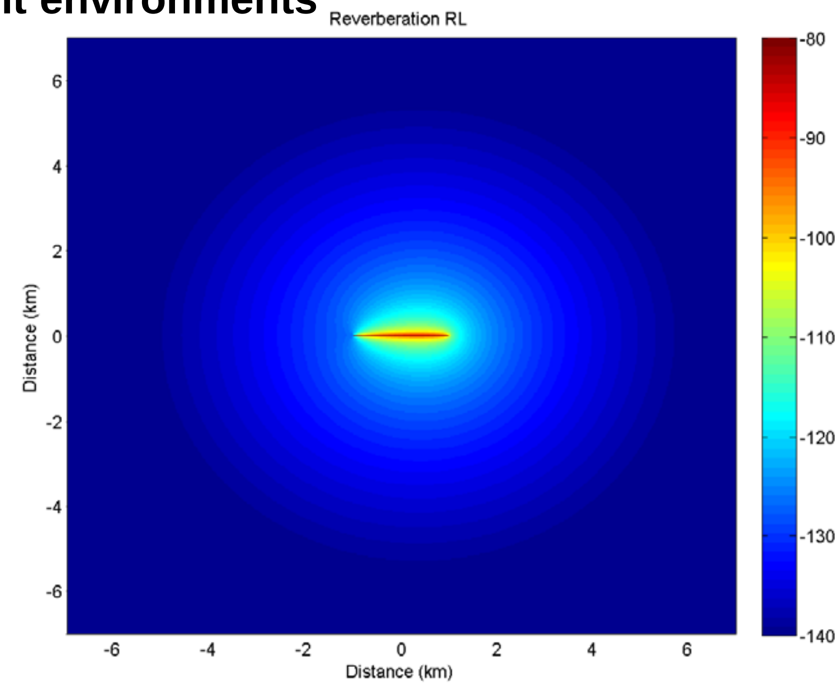
- **The helm will be operated at a constant speed* and constant depth***
- **At the present position**
  - **For the estimated source position and speed**
    - **Either 1) known or 2) obtained from comms or 3) estimated by tracker running on the direct blast contact and using accurate timing**
  - **For the estimated receiver position and speed**
    - **Estimated by a tracker running on the first non-direct blast target**
  - **For a number of possible trajectories** *seconds_future* **in the future evaluated at** *num_times*
  - **Search over possible trajectories (determined by** *range_headings* **and** *num_headings***)**
    - **Max SNR(L^{∞})**
    - **Maximum average SNR (L^{2})**
    - **Maximum minimum SNR ($L^{-\infty}$)**
  - **Use** MOOS-IvP **to output DESIRED_HEADING**

Maximize SNR Technical Approach Continued

- **The helm will be operated at a constant speed* and constant depth***
- **Constant speed restriction can be eliminated by searching over possible speeds and minimizing a 2D objective function**
    - Reflector
- **The constant depth restriction can be eliminated by searching over desired depths for various target hypotheses**
    - **Known target depth**
    - **Known target depth range**
    - **Target depth likelihood**
    - **Use fast RD prop code, most likely BELLHOP**
- **Even current "lat-long" approach can be extended to RD**
    - **Sound speed profile**
        - uCtdSim2
    - **Bathymetry**
        - uBathy

Model Based Objective Function
RL

- **Use Harrison's formulae inspired by Weston for the rapid estimation of bistatic reverb in iso-velocity range independent environments**



- **TL**

$$I(r_1) = \frac{2}{rH} \int_0^{\pi/2} \left| R(\theta) \right|^{r_1 \tan\theta / H} d\theta$$

- **Area**

$$A(r_1, r_2, \Theta) = \delta t \delta \phi \frac{2 c r_1 r_2^2}{(ct)^2 - L^2}$$

- **RL**

$$I_{rev}(r_1, r_2) = S \frac{4}{r_1 r_2 H^2} \int_0^{\pi/2} d\theta_1 \int_0^{\pi/2} d\theta_2 \left| R(\theta_1) \right|^{r_1 \tan\theta/H} S\; S(\theta_1, \theta_2, \Theta) A(r_1, r_2, \Theta) \left| R(\theta_2) \right|^{r_2 \tan\theta/H}$$

Model Based Objective Function EL

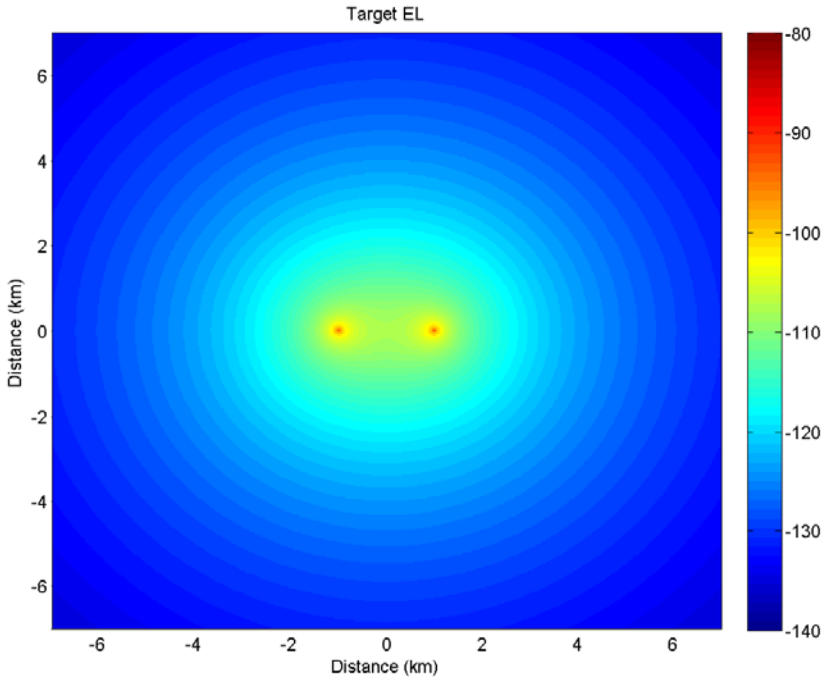
- **For Echo Level use round-trip TL and a target strength TS**

- **TL**

$$I(r_1) = \frac{2}{rH} \int_0^{\pi/2} \left| R(\theta) \right|^{r_1 \tan\theta / H} d\theta$$

- **TS**

$$\mathbf{TS} = 20\log 10\left(a/2\right)$$

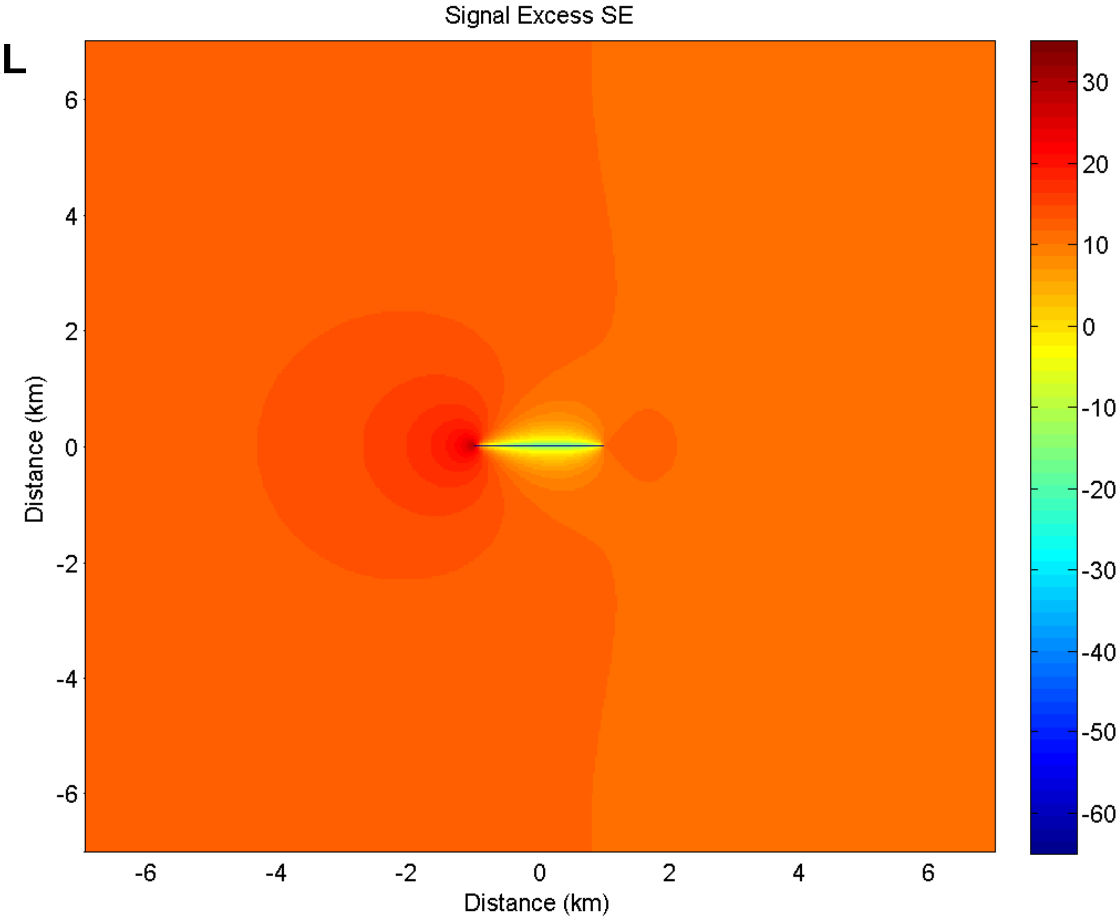


- **EL**

$$I_{target}(r_1, r_2) = \mathbf{TS} \frac{4}{r_1 r_2 H^2} \int_0^{\pi/2} d\theta_1 \int_0^{\pi/2} d\theta_2 \left| R(\theta_1) \right|^{r_1 \tan\theta / H} \left| R(\theta_2) \right|^{r_2 \tan\theta / H}$$

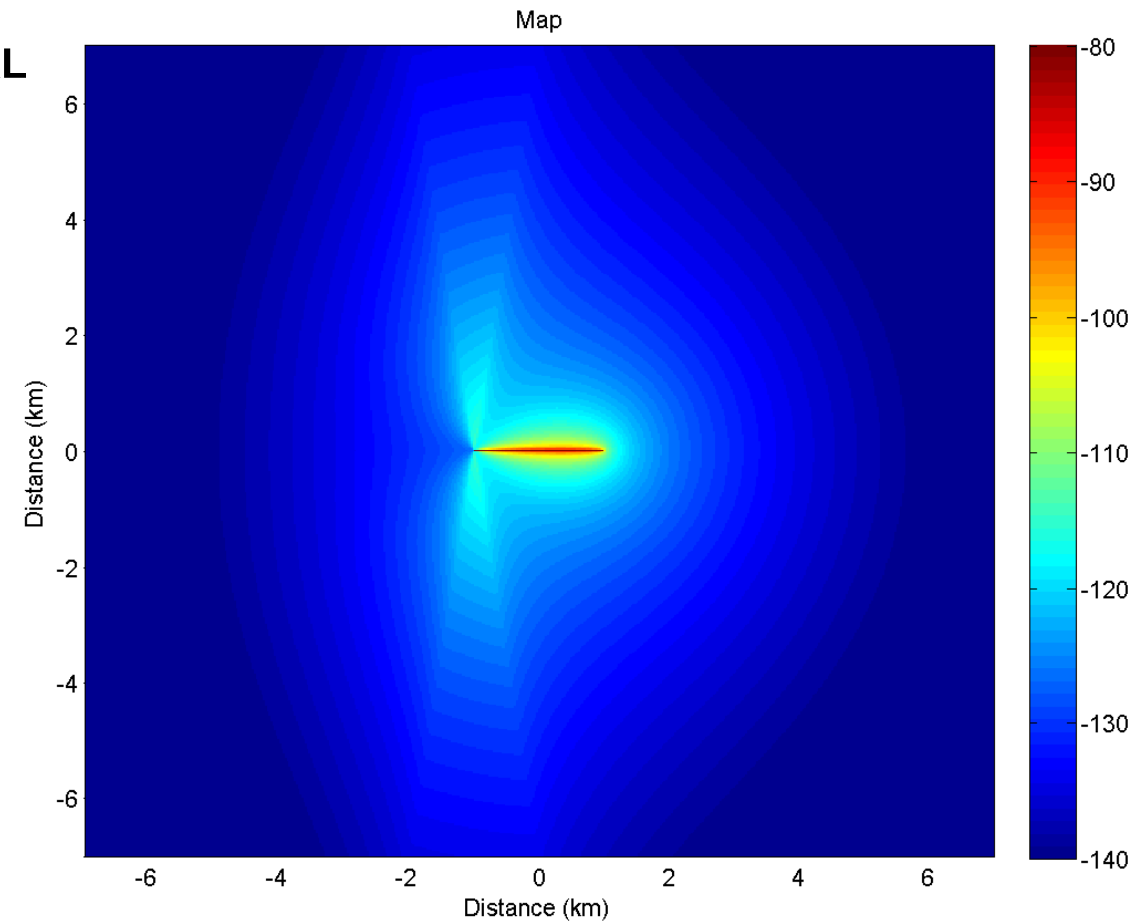
SNR Objective Function in Target Location Space

SNR=EL-RL



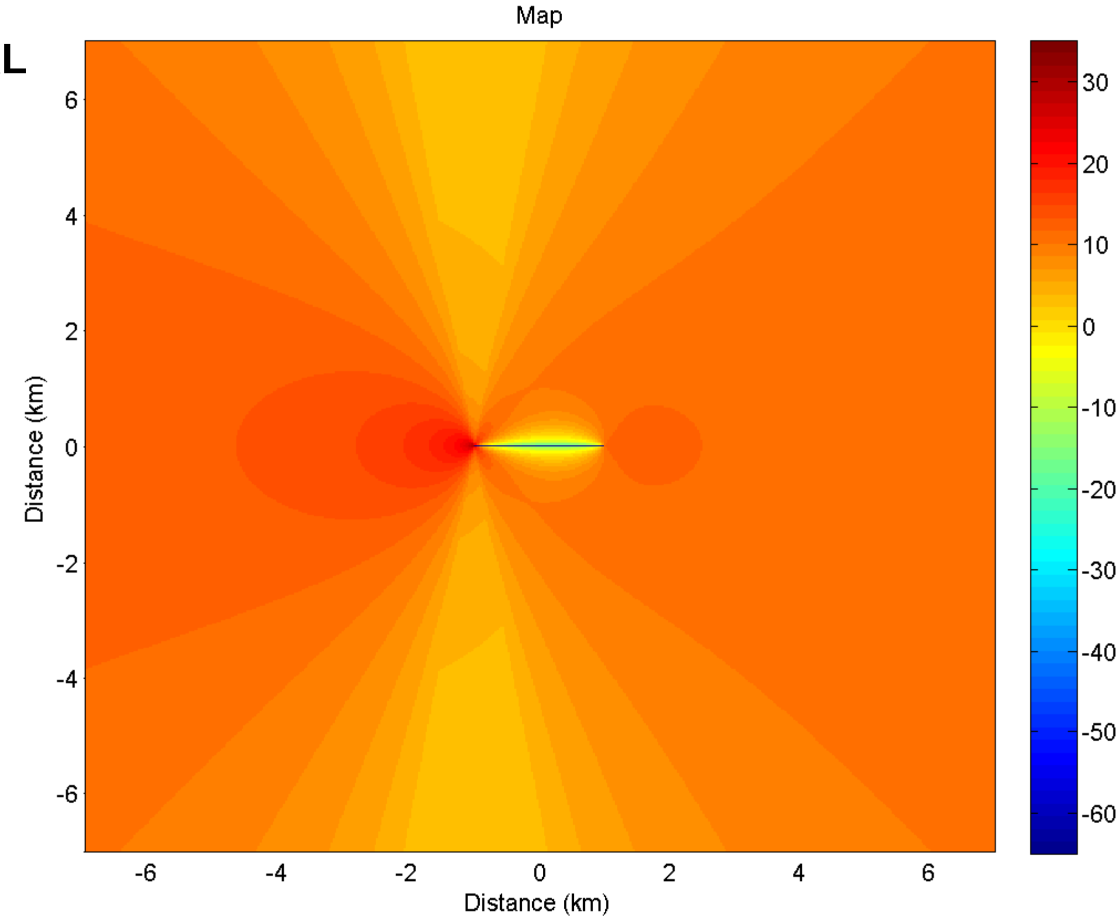
RL: Reverberation with BENS Aperture in Target Location Space

SNR=EL-RL



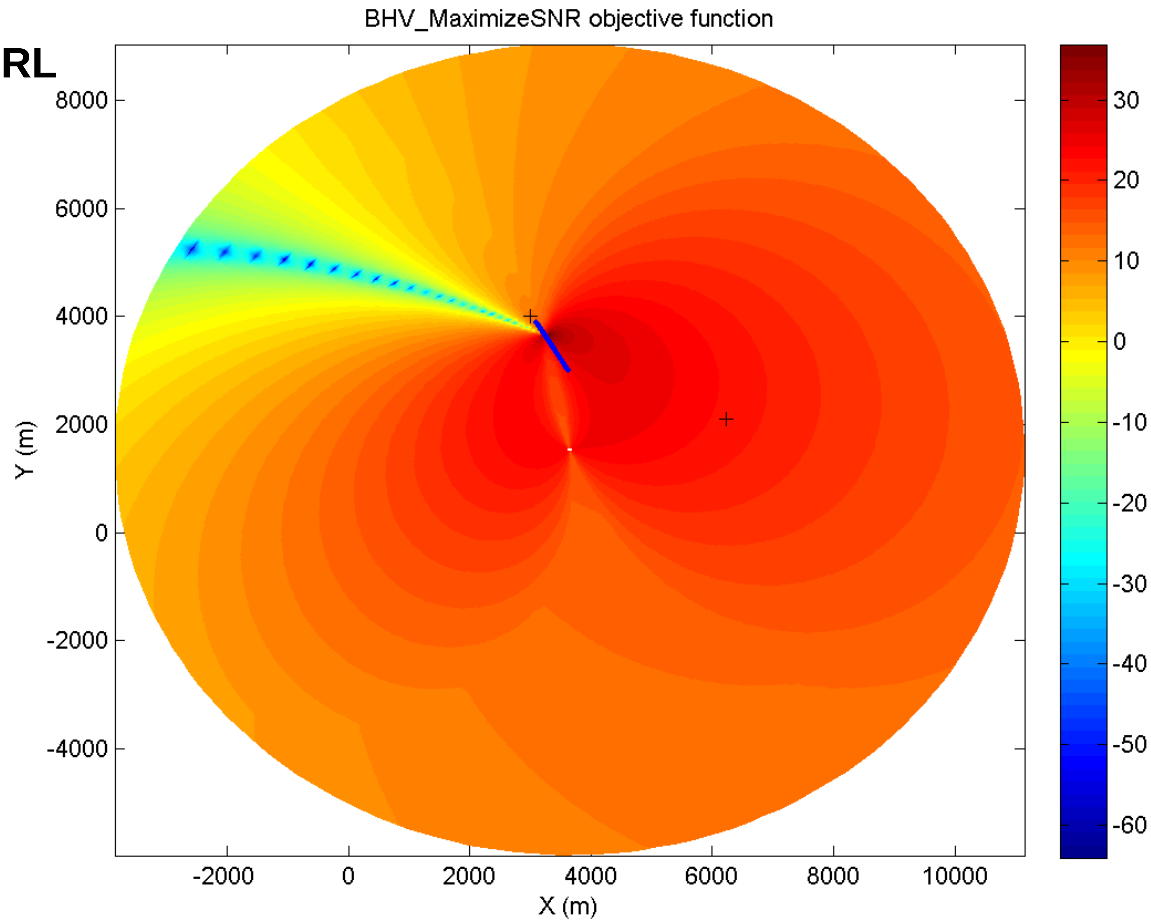
SNR Objective Function with BENS Aperture in Target Location Space

SNR=EL-RL



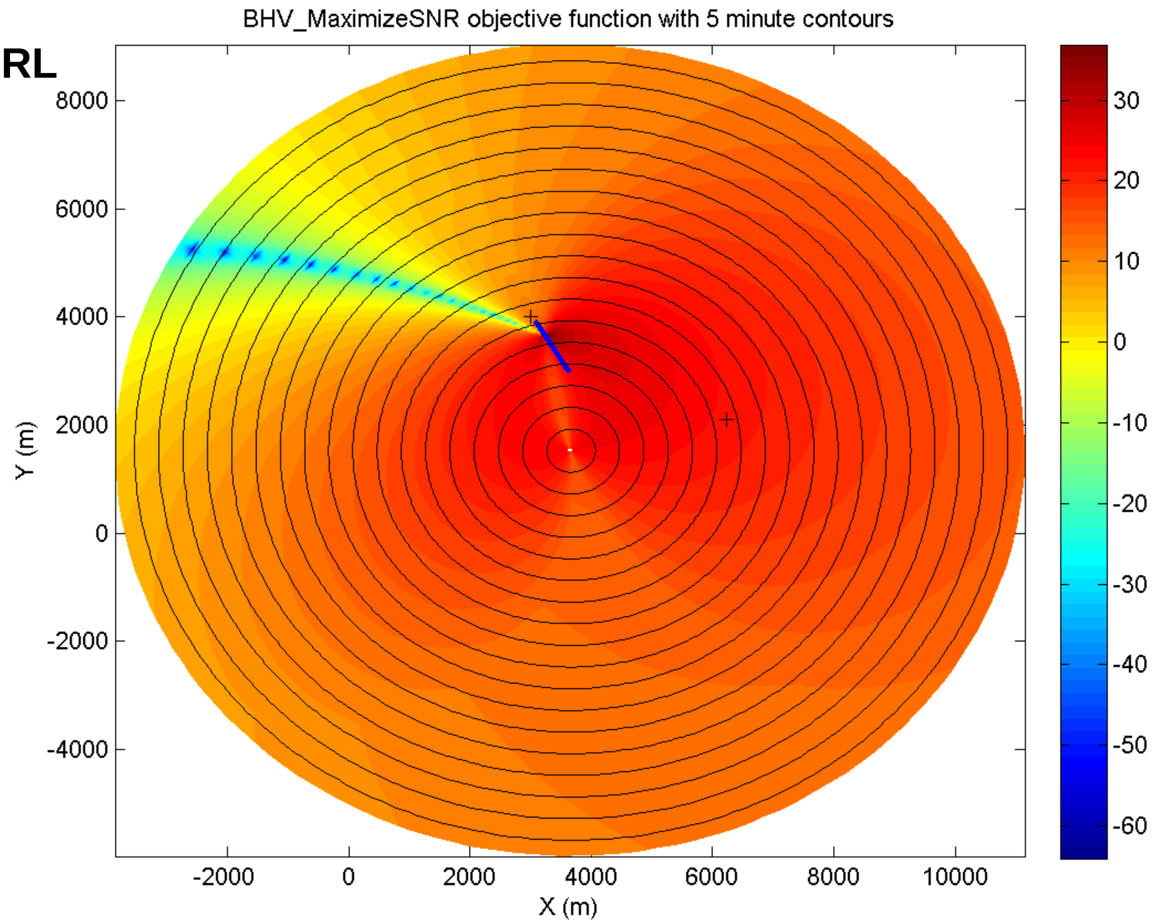
SNR Objective Function with BENS Aperture in Possible Receiver Space

SNR=EL-RL



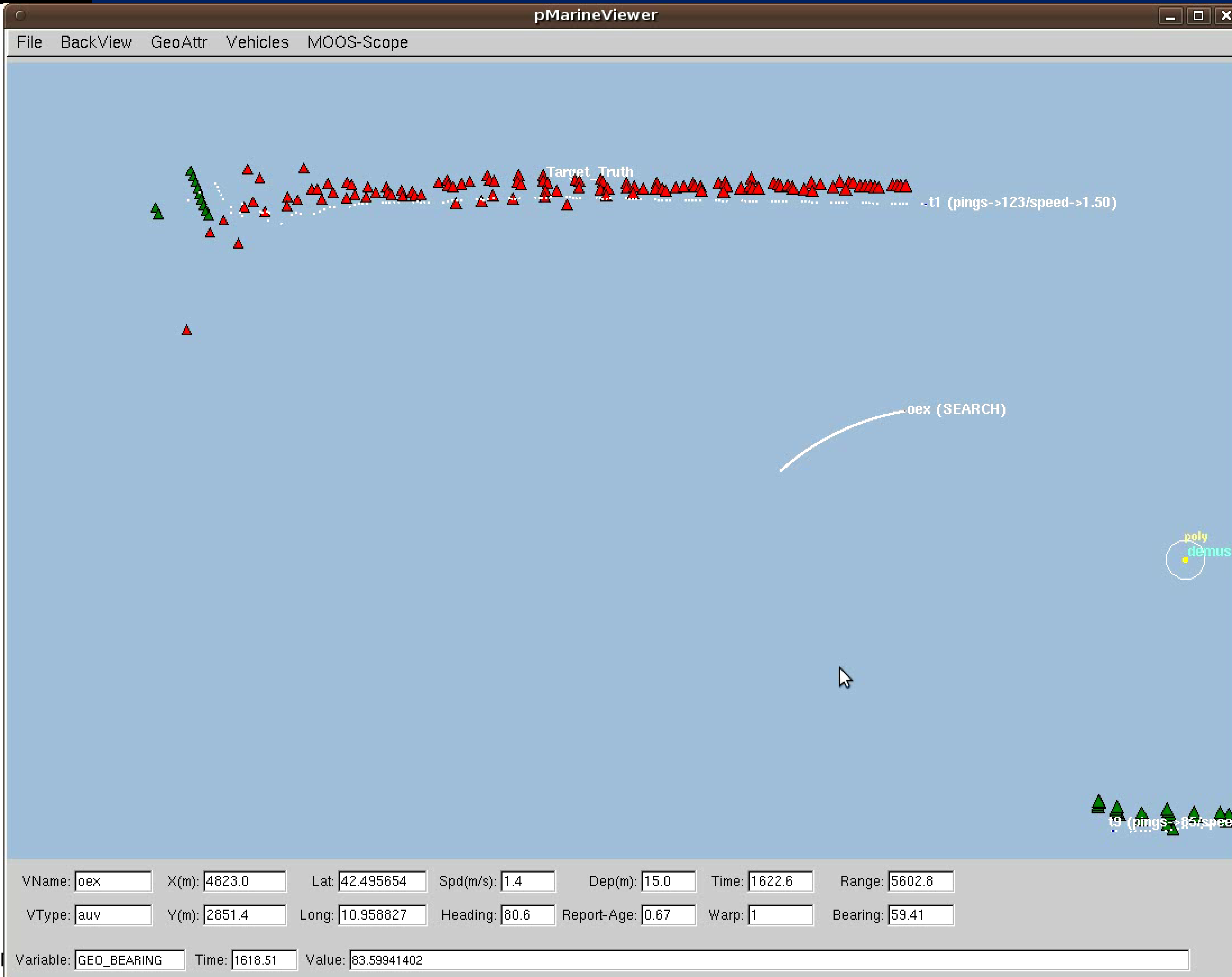
SNR Objective Function with BENS Aperture in Possible Receiver Space

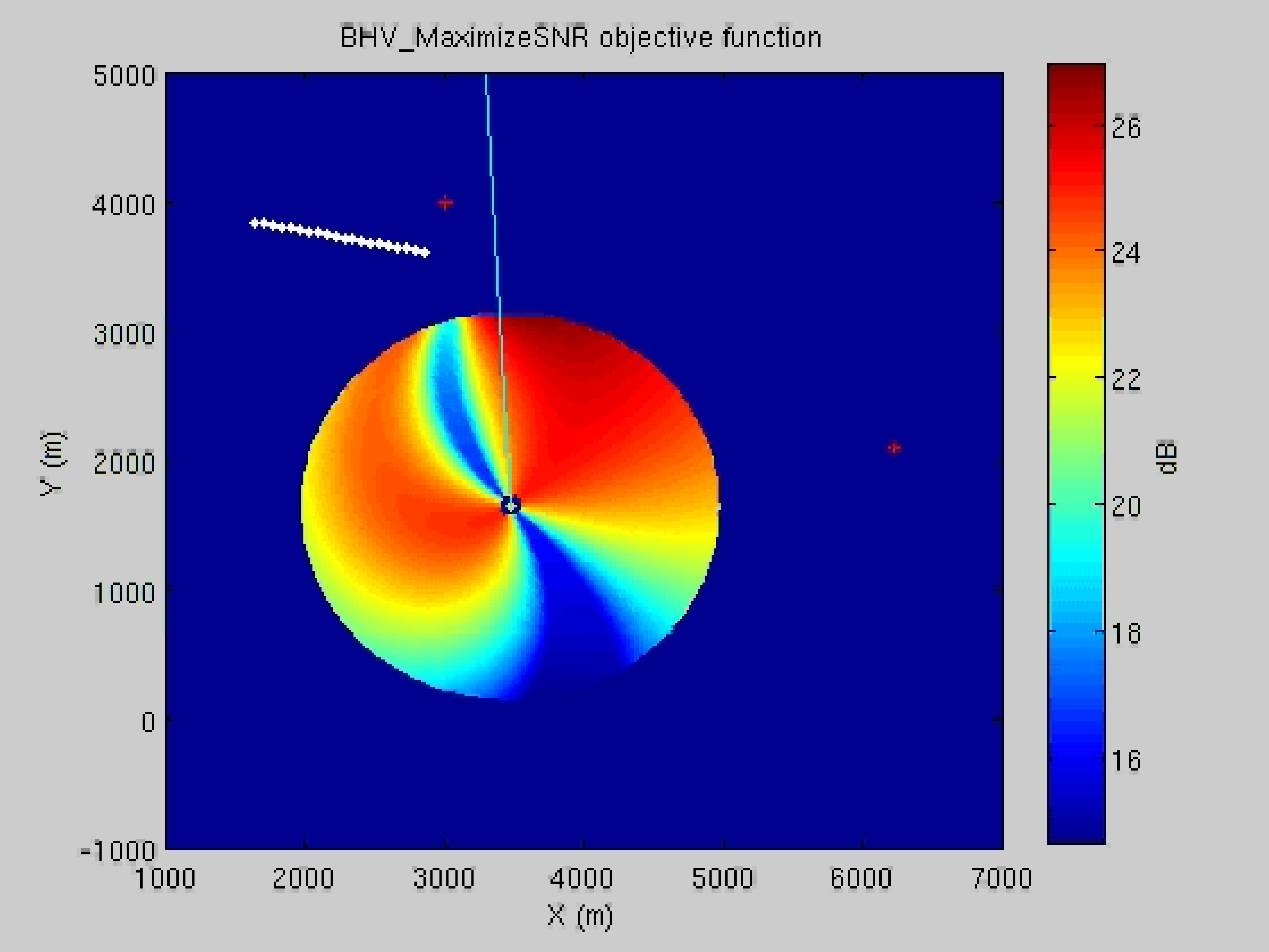
SNR=EL-RL



BHV_MaximizeSNR on Moving Target

- **Moving Target starts at [1000,4000] sailing 2.5 kts east**
- **AUV Loitering at [3800,1900]**
- **AUV switches modes from MANUEVER to PROSECUTE**
  - **Currently with a MOOSPoke, need to automate probably on SNR similar to BHV_BroadsideSNR**
- **AUV tries to maximize average SNR on target**
- **Parameters of BHV_MaximizeSNR**
  - *num_times*=**20**
  - *seconds_future*=**500**
  - *num_headings*=**181**
  - *range_headings*=**360**


pMarineViewer
File
BackView
GeoAttr
Vehicles
MOOS-Scope
Target_Truth
t1 (pings->123/speed->1.50)
oex (SEARCH)
poly
demus
VName: oex
X(m): 4823.0
Lat: 42.495654
Spd(m/s): 1.4
Dep(m): 15.0
Time: 1622.6
Range: 5602.8
VType: auv
Y(m): 2851.4
Long: 10.958827
Heading: 80.6
Report-Age: 0.67
Warp: 1
Bearing: 59.41
Variable: GEO_BEARING
Time: 1618.51
Value: 83.59941402


BHV_MaximizeSNR objective function
5000
4000
3000
2000
1000
0
-1000
Y (m)
1000
2000
3000
4000
5000
6000
7000
X (m)
26
24
22
20
18
16
dB

BHV_MaximizeSNR on Stationary Target

- **Stationary Target starts at [3000,4000] 0 kts**
- **AUV Loitering at [3800,1900]**
- **AUV switches modes from MANUEVER to PROSECUTE**
    - **Currently with a MOOSPoke, need to automate probably on SNR similar to BHV_BroadsideSNR**
- **AUV tries to maximize average SNR on target**
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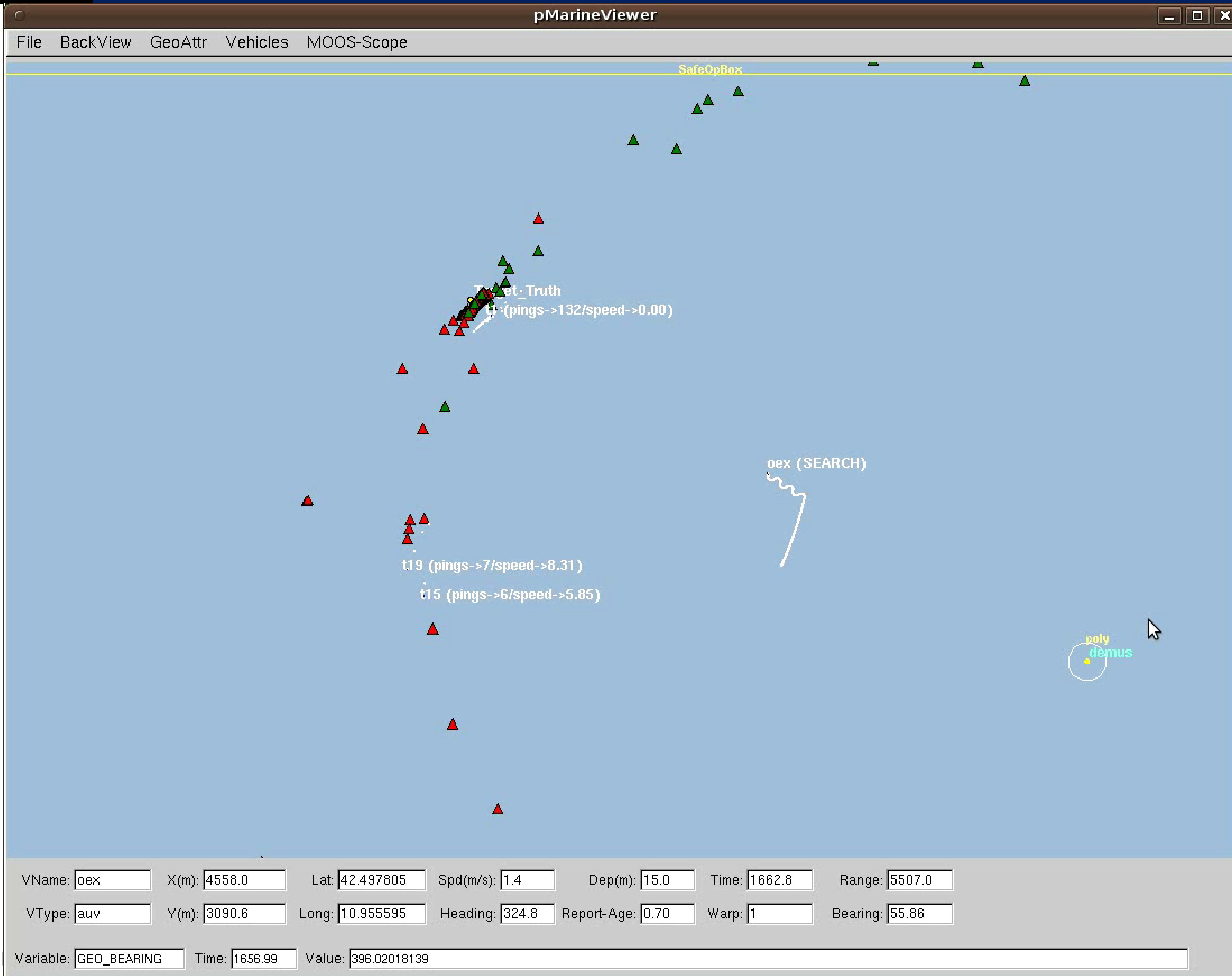
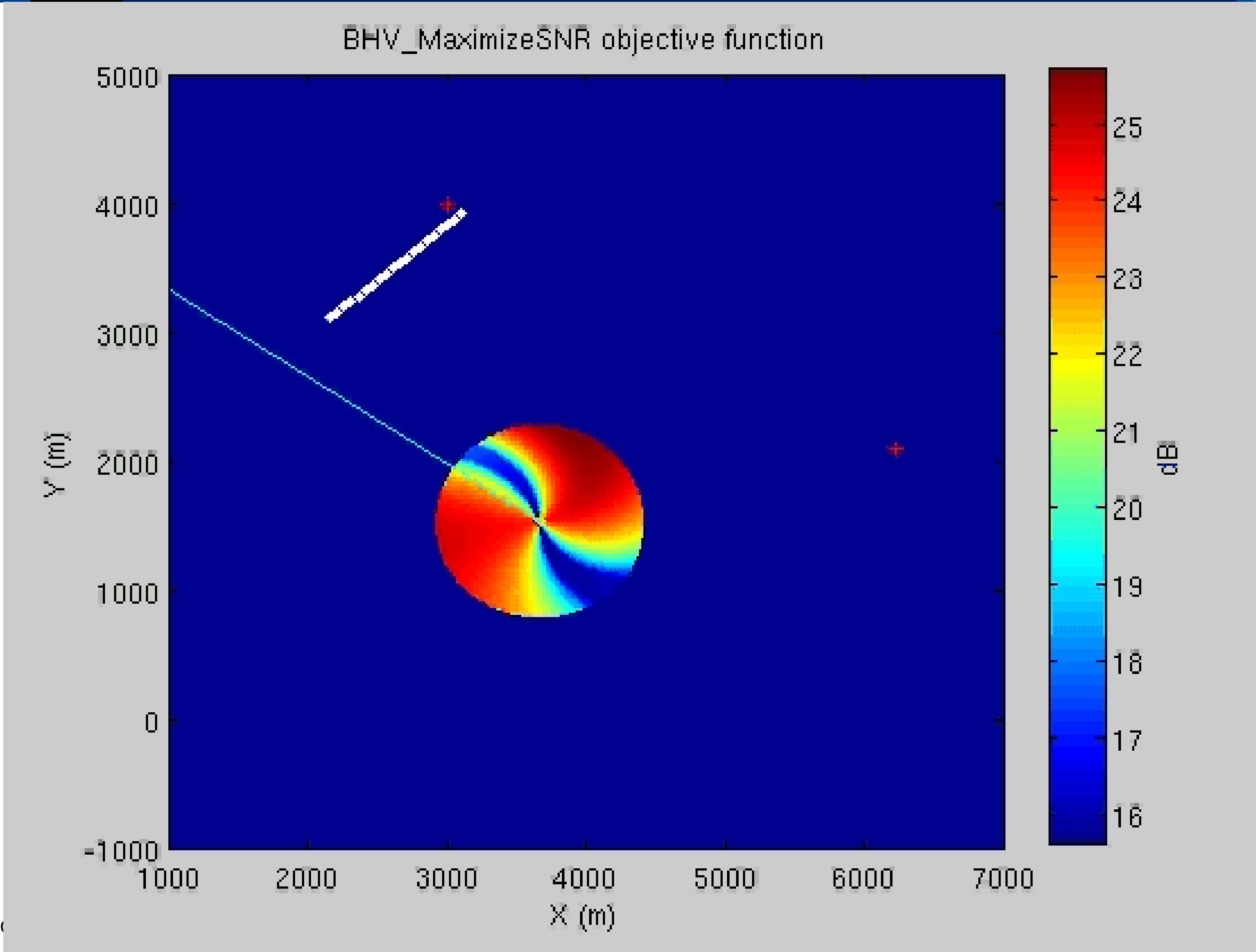

pMarineViewer
File BackView GeoAttr Vehicles MOOS-Scope
SafeOpBox
(pings->132/speed->0.00)
oex (SEARCH)
t19 (pings->7/speed->8.31)
t15 (pings->6/speed->5.85)
poly
demus
VName: oex
X(m): 4558.0
Lat: 42.497805
Spd(m/s): 1.4
Dep(m): 15.0
Time: 1662.8
Range: 5507.0
VType: auv
Y(m): 3090.6
Long: 10.955595
Heading: 324.8
Report-Age: 0.70
Warp: 1
Bearing: 55.86
Variable: GEO_BEARING
Time: 1656.99
Value: 396.02018139


BHV_MaximizeSNR objective function
5000
4000
3000
2000
1000
0
-1000
Y (m)
1000
2000
3000
4000
5000
6000
7000
X (m)
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24
23
22
21
20
19
18
17
16
dB

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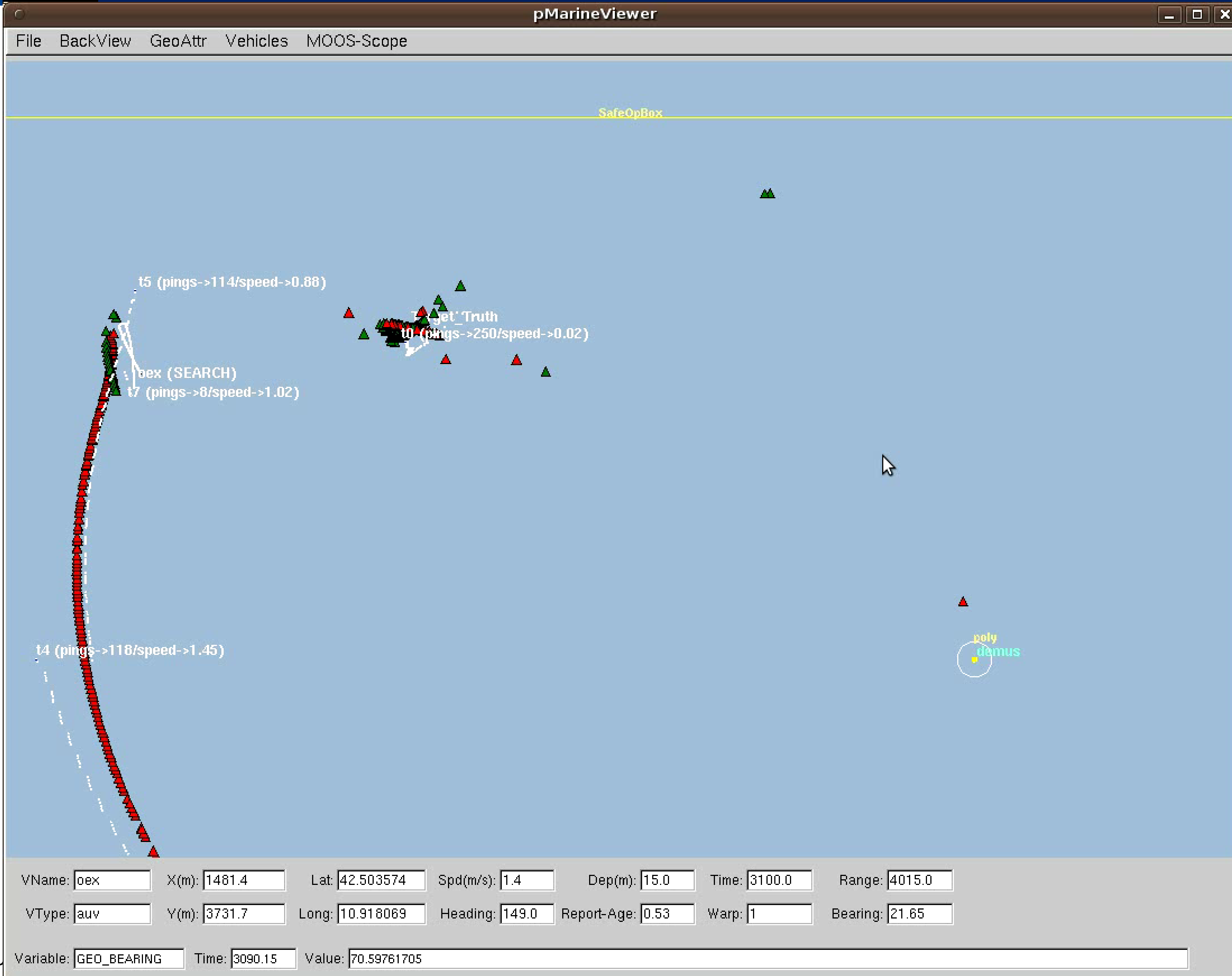
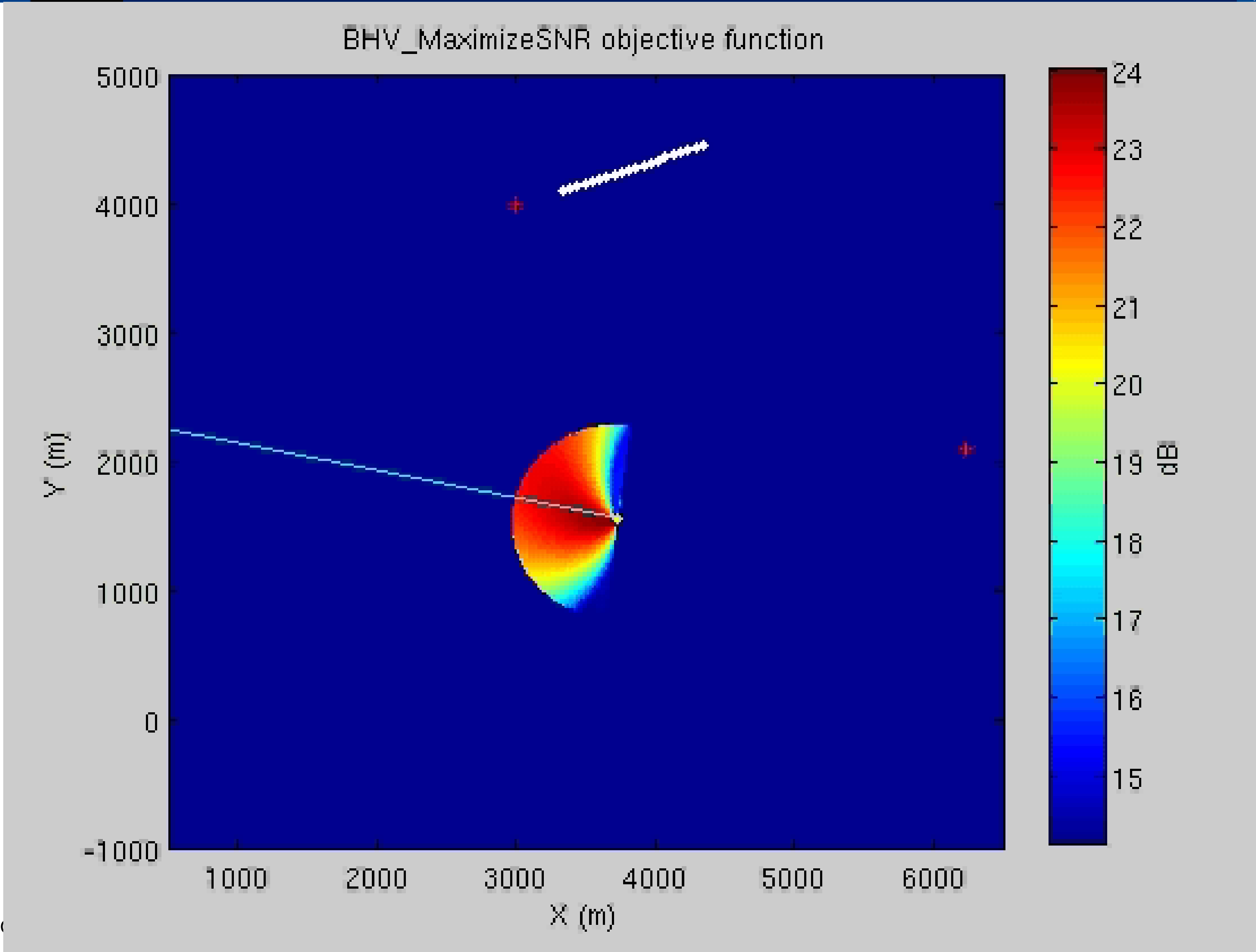
NATO
OTAN

NURC




BHV_MaximizeSNR objective function
5000
4000
3000
2000
1000
0
-1000
Y (m)
1000
2000
3000
4000
5000
6000
X (m)
24
23
22
21
20
19
18
17
16
15
dB

BHV_MaximizeSNR Preliminary Conclusions

- Behaviour seeks to keep target on or near broadside
- Behaviour simultaneously tries to close range
- Behaviour avoids “blackout region”
- Behaviour can demonstrate emergent behaviour of helm ambiguous heading oscillation (damped by BHV_MemoryTurnLimit) when it is allowed to consider completely reversing course
    - Occurs when vehicle crosses source-target axis where the objective function becomes ambiguous (symmetric)
- Behaviour tries to sail “almost” directly towards target when the *seconds_future* parameter encompasses the estimated target position

Maximize SNR Technical Approach Continued

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    - **Target depth likelihood**
    - **Use fast RI prop code, most likely KRAKEN**
- **Even current "lat-long" approach can be extended to RD**
    - **Sound speed profile**
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    - **Bathymetry**
        - uBathy

Model Based Depth Objective Function
TL

- Use Harrison's formulae inspired by Weston for the rapid estimation of bistatic reverb in iso-velocity range independent environments

- TL from source to target

$$p(z_s, z_T, r_1)/p(1) \propto \sqrt{\frac{2\pi}{r_1}} \sum_{n=1}^{N} k_n^{-1/2} \phi_n(z_s) \phi_n(z_T) e^{ik_n r_1}$$

- TL from target to receiver

$$p(z_T, z_r, r_2)/p(1) \propto \sqrt{\frac{2\pi}{r_2}} \sum_{m=1}^{N} k_m^{-1/2} \phi_m(z_T) \phi_m(z_r) e^{ik_m r_1}$$

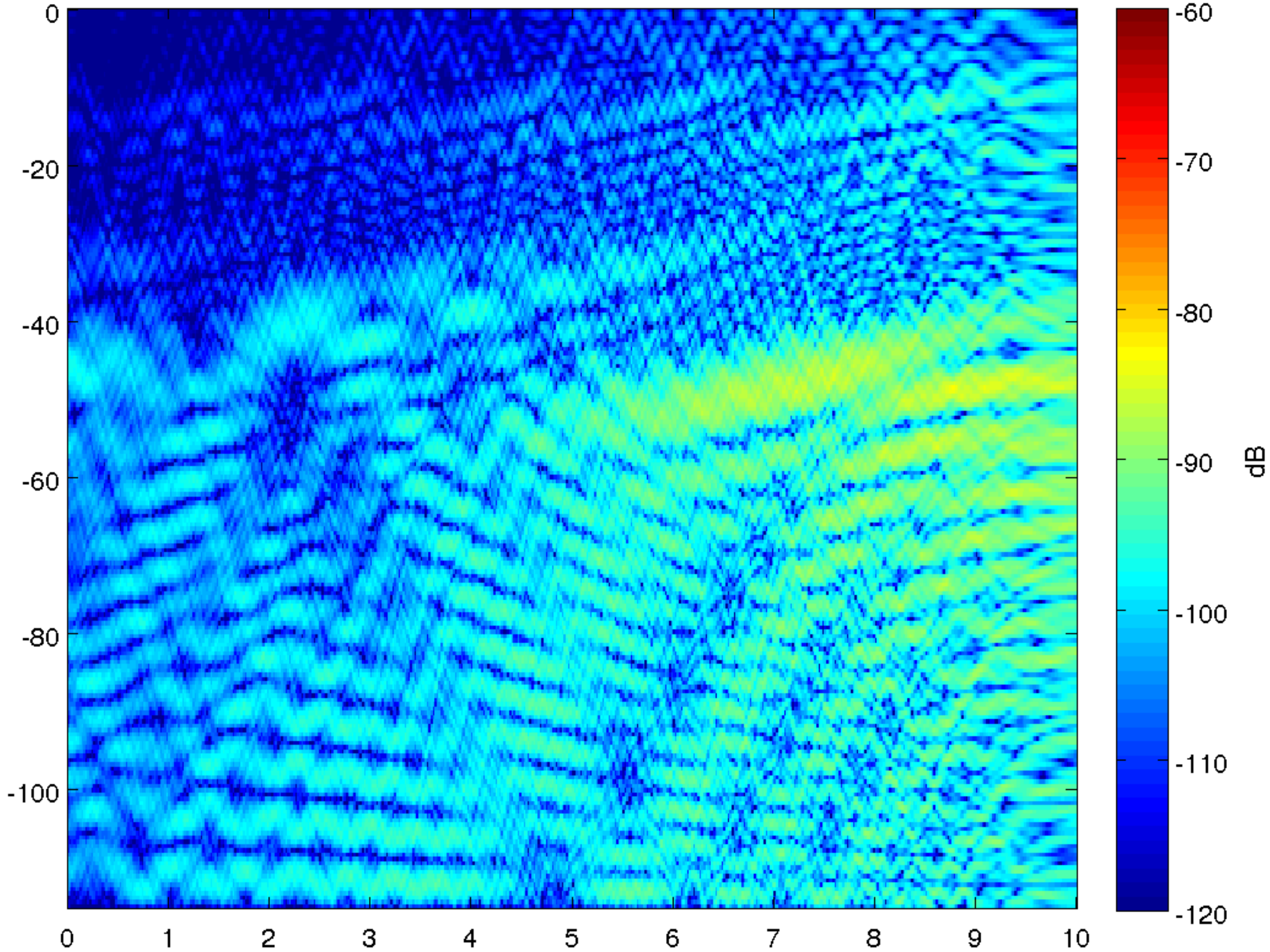
- Total TL integrated over uncertain target depth

$$p(z_s, z_T, z_r, r_1, r_2) \propto \sqrt{\frac{4\pi^2}{r_1 r_2}} \sum_{m=1}^{N} \sum_{m=1}^{N} k_n^{-1/2} k_m^{-1/2} \phi_n(z_s) \phi_m(z_r) e^{i(k_m r_1 + k_n r_2)} \int_{-H}^{0} \phi_m(z_T) \phi_m(z_T) p(z_T) dz_T$$

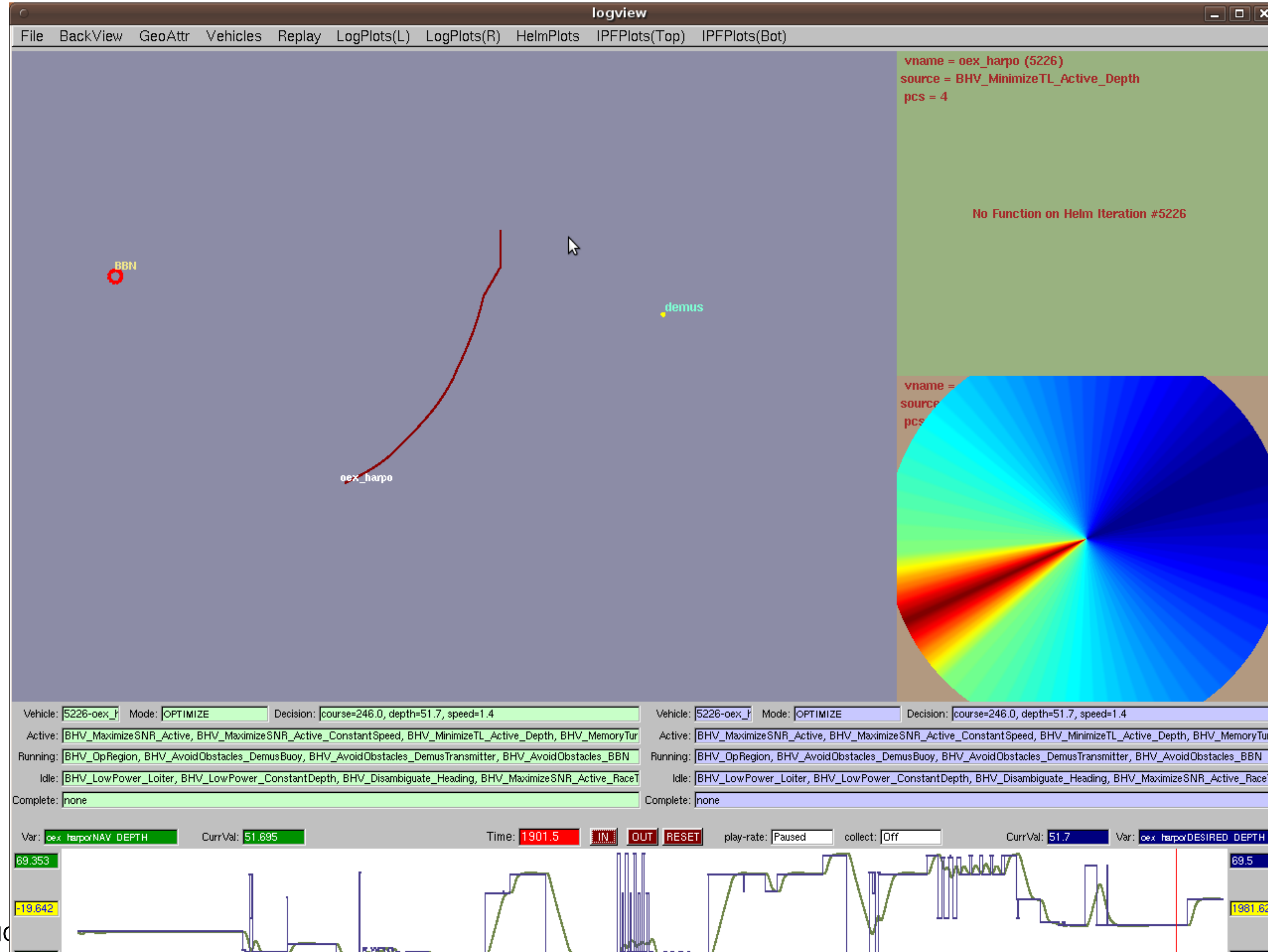
$$\propto \sqrt{\frac{4\pi^2}{r_1 r_2}} \sum_{m=1}^{N} k_m^{-1} \phi_m(z_s) \phi_m(z_r) e^{ik_m(r_1 + r_2)}$$

Model Based Depth Objective Function

TL



Combined MaximizeSNR and MinimizeTL Simulation



MimimizeTL_Depth Behaviour
Preliminary Conclusions

- Very similar to Toby Schneider's work using Bellhop and trying to minimize TL
  - Using Kraken instead of Bellhop
  - Field computed inside behaviour using modes
  - Uses existing .mod file
- Currently the depth of the maximum transmission gain averaged over a number of look-ahead times is used to determine the optimum depth
- Helm designs an objective function based only on this optimum depth
  - Could pass the entire time averaged transmission gain to the helm via piecewise linear map
- This work could be made entirely consistent with the X-Y maximized SNR behaviour by calculating signal excess as a function of depth rather than TL

AUV Model Based Autonomy
Overall Conclusions

- AUV autonomy for ASW is an emerging research area
- Typical solutions at the moment are driven by ideas
    - What the behaviour designer feels would be a robust algorithm with a good chance of demonstrating good performance
- Measures of effectiveness are still being determined
- Autonomy based on towed array sensors can be very sensitive
    - Autonomy algorithm adjusts helm, new heading leads to heading or location ambiguity of a contact
    - Moving contacts lead to broken tracks, leading to control instability as new detection and track on the contact of interest must be formed
- Clutter and false alarms will pose major challenges
- Fusion of information between collaborating assets will be a major challenge

Technical Risks/Remaining Work

- **Maximize SNR**
  - **Have GROUCHO process the BENS array data using** pProcessSlita**, generate contacts using** pBistaticLocator**, and have** pKalmanTracker **generate useful tracks that persist long enough for the behaviour to act on**
  - **Write the software that will allow the behaviour state to change from loiter to maximize snr upon the appearance of a track of sufficient quality**
- **Overall**
  - **Make sure that MOOSIvP works with the** iOEX **frontseat driver for even the simplest missions**

Backup Slides

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Elongated Target in Target Location Space

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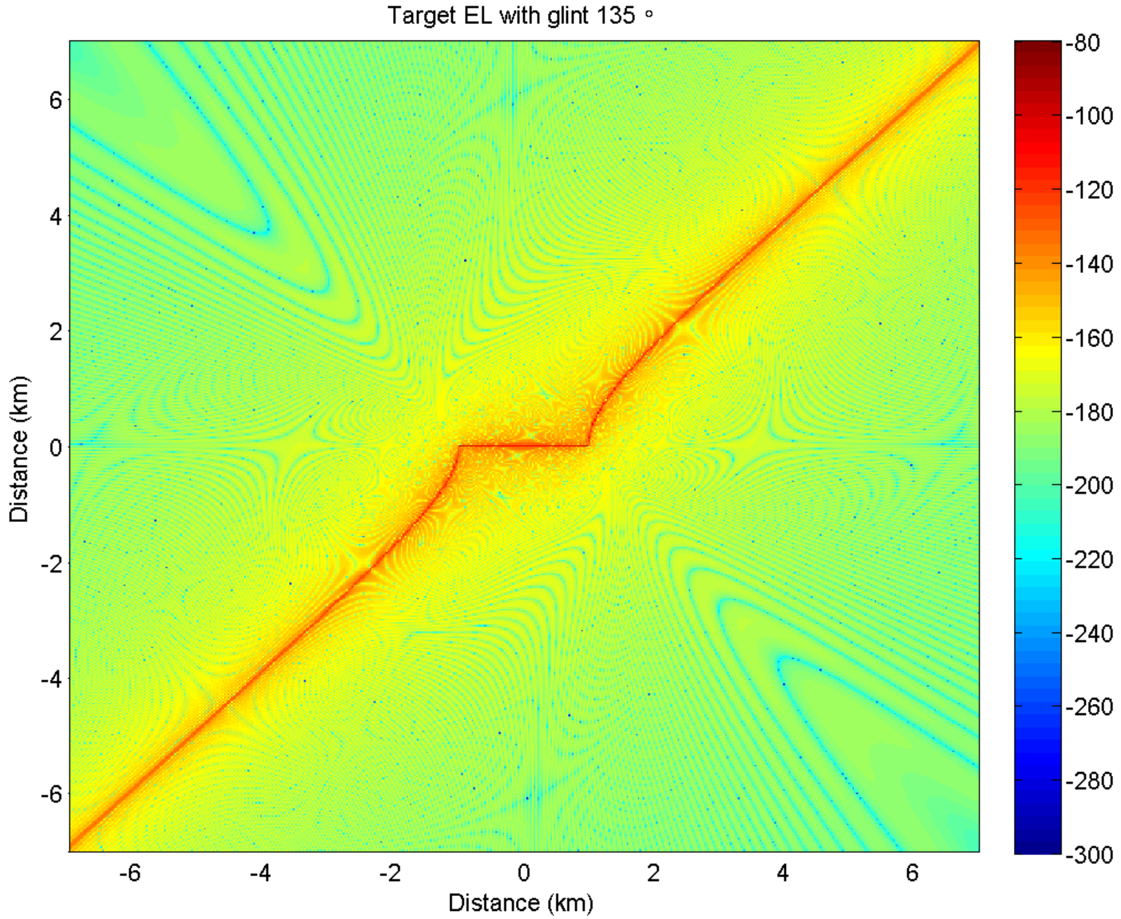
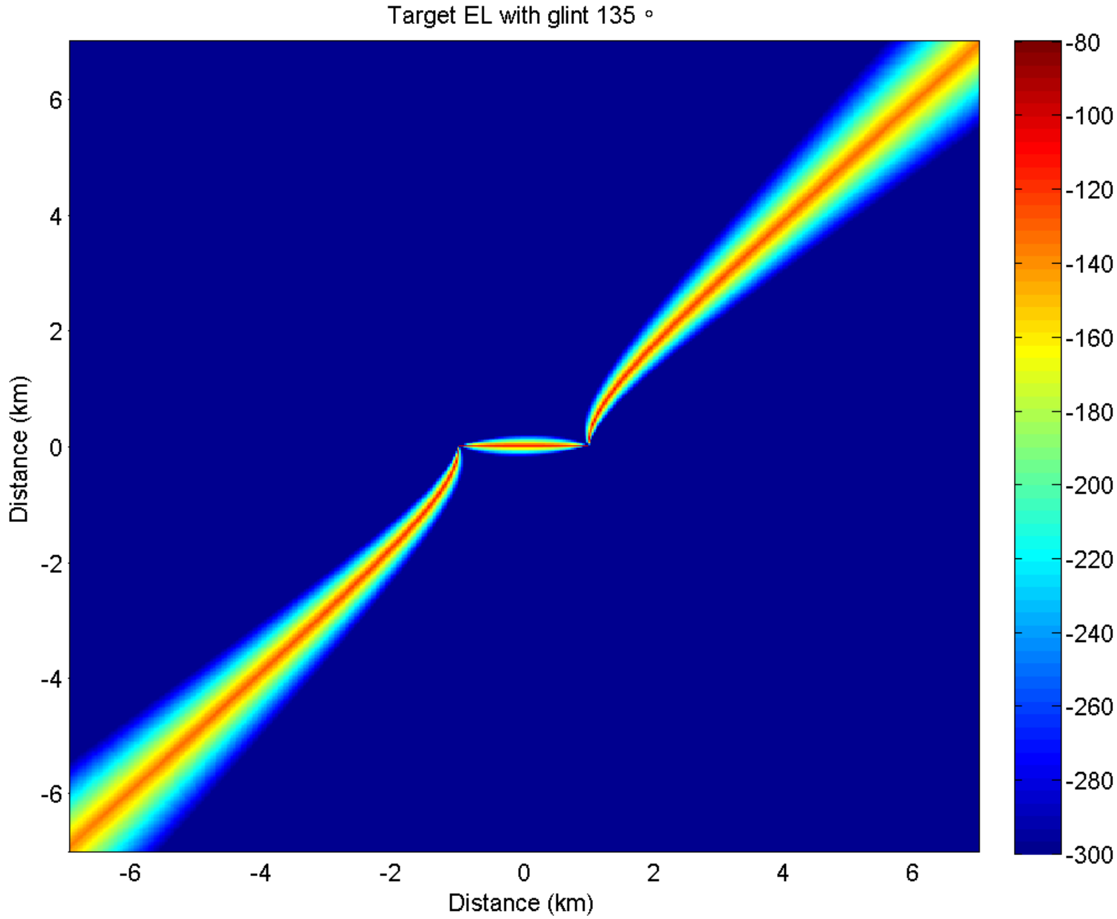


$$\mathbf{TS} = \mathbf{TS}_{broadside} + 20\log 10\left(\left|\sin c\left(kL\left(\cos\theta_{refl} - \cos\theta_{obs}\right)/2\right)\right|\right)$$

Elongated Target in Target Location Space



$$\mathbf{TS} = \mathbf{TS}_{broadside} + 20\log 10\left(\exp\left(-kL\left|\left(\cos\theta_{refl} - \cos\theta_{obs}\right)\right|/2\right)\right)$$

SNR Objective Function with BENS Aperture in Possible Receiver Space

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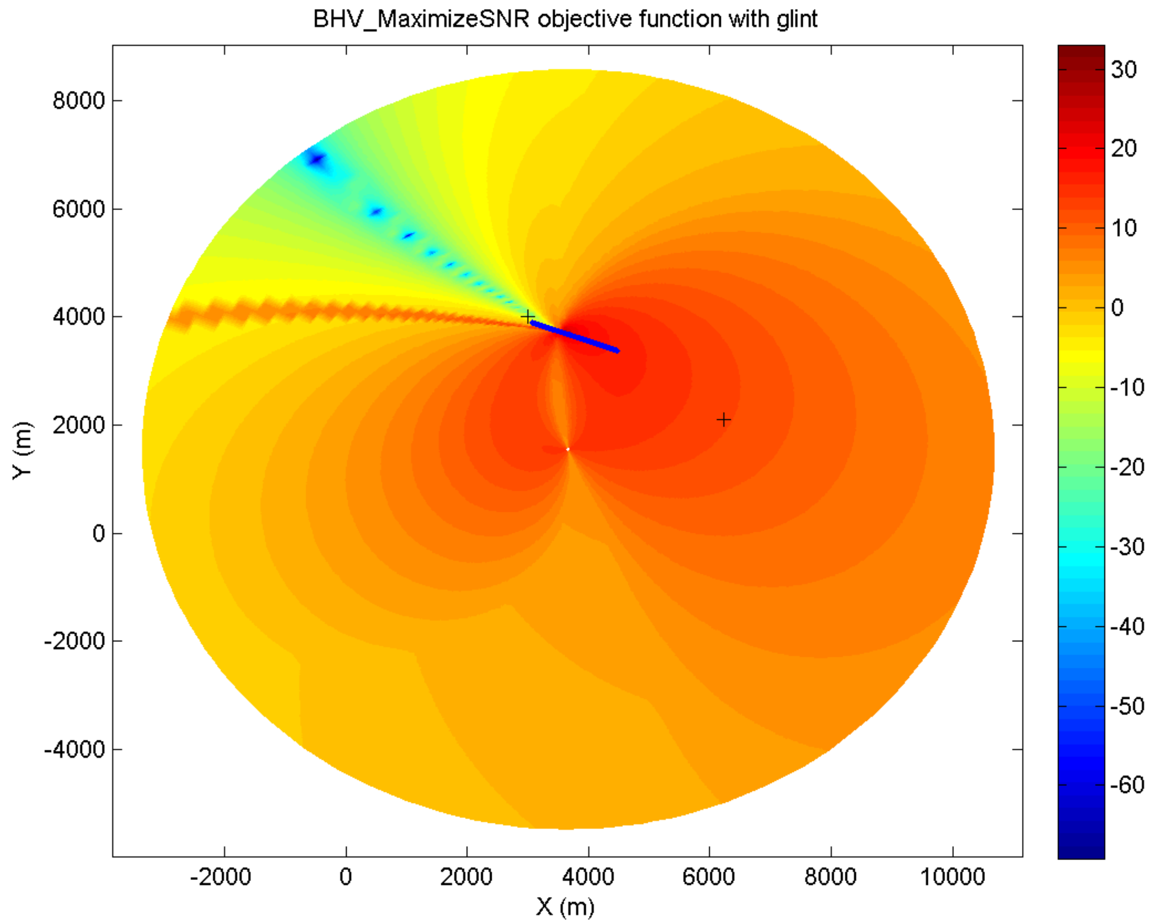

RL: Reverberation in Target Location Space

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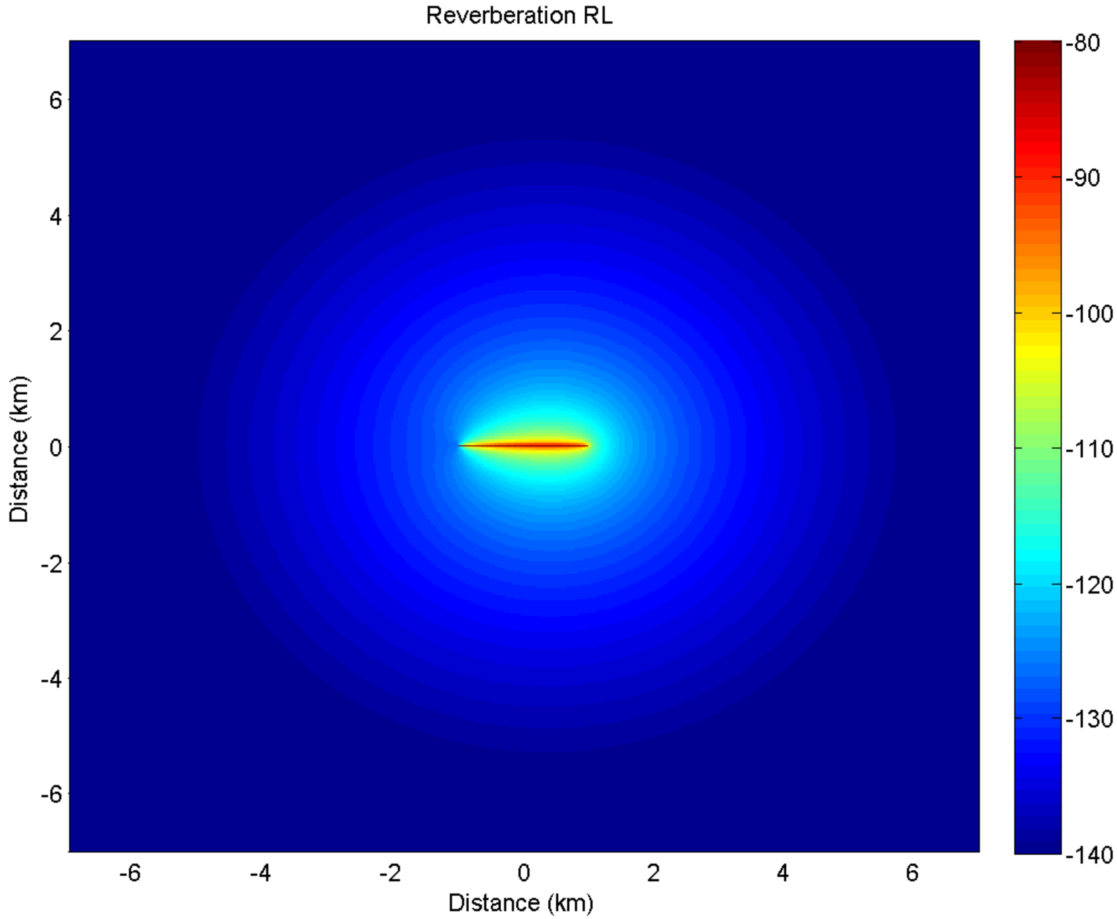

EL: Omni-Directional Target in Target Location Space

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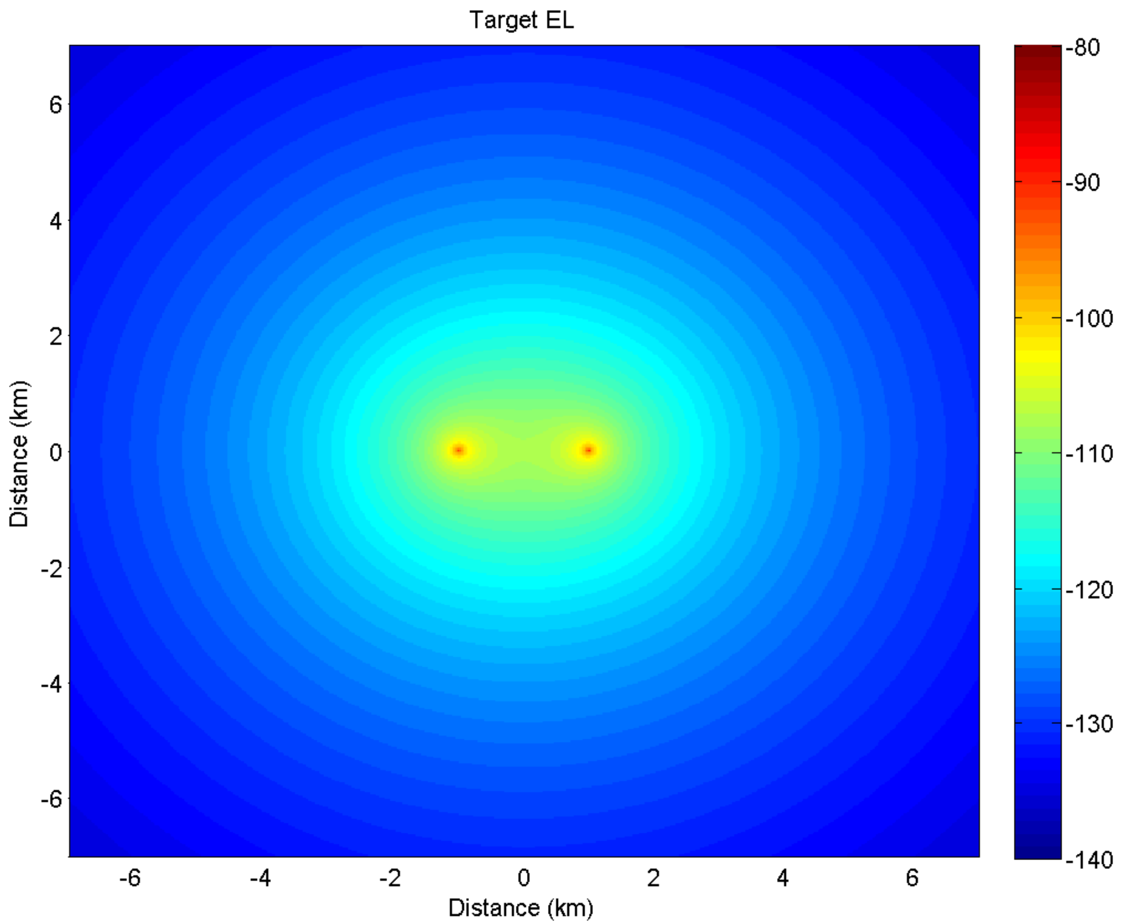

SNR Objective Function in Target Location Space with Glint

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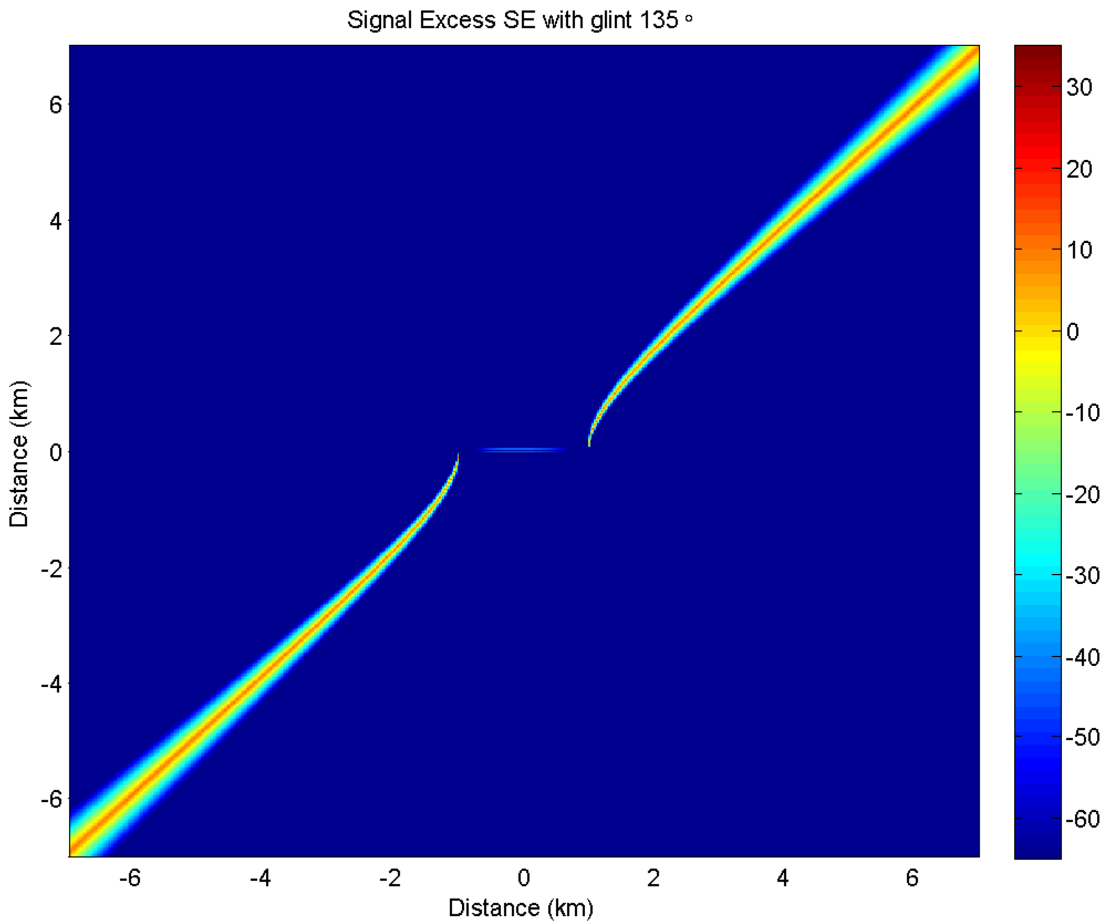
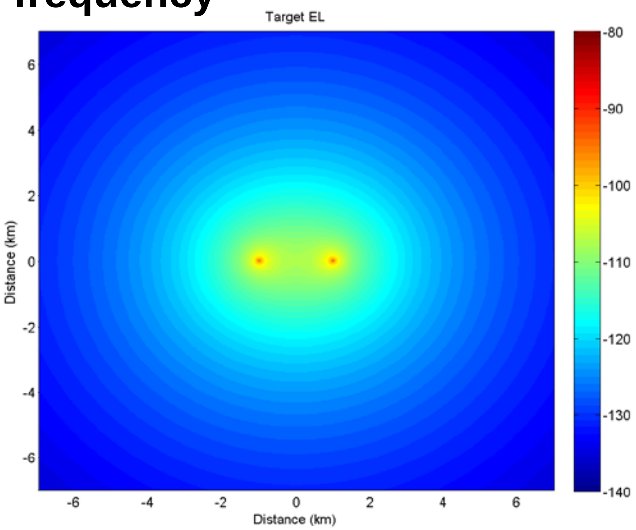


Reverberation Modeling Approach Continued

▪ **For Echo Level use round-trip TL plus a specular target model that gives a glint width determined by the hull length and the frequency**



▪**TL**

$$I(r_1) = \frac{2}{rH} \int_0^{\pi/2} \left| R(\theta) \right|^{r_1 \tan\theta / H} d\theta$$

▪**TS**

$$\mathbf{TS} = \mathbf{TS}_{broadside} + 20\log 10\left(\left| \sin c\left(kL\left(\cos\theta_{refl} - \cos\theta_{obs} \right) / 2 \right) \right| \right)$$

▪**EL**

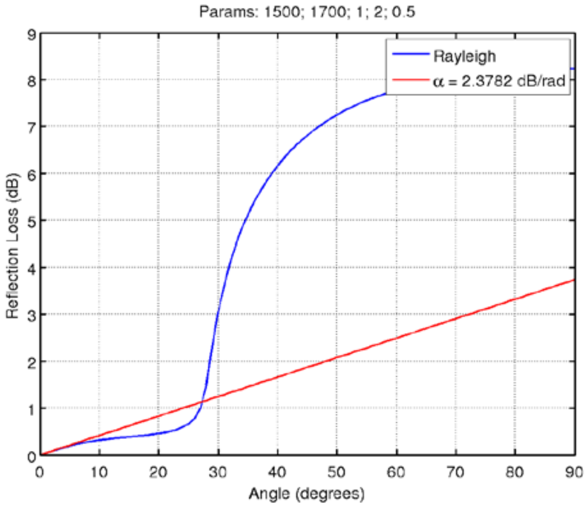
$$I_{target}(r_1, r_2) = \mathbf{TS} \frac{4}{r_1 r_2 H^2} \int_0^{\pi/2} d\theta_1 \int_0^{\pi/2} d\theta_2 \left| R(\theta_1) \right|^{r_1 \tan\theta/H} \left| R(\theta_2) \right|^{r_2 \tan\theta/H}$$

Reverberation Modeling Approach

- **Use Harrison's formulae inspired by Weston for the rapid estimation of bistatic reverb in iso-velocity range independent environments**

- **TL**

$$I(r_1) = \frac{2}{rH} \int_0^{\pi/2} \left| R(\theta) \right|^{r_1 \tan\theta / H} d\theta$$



- **Area**

$$A(r_1, r_2, \Theta) = \delta t \delta \phi \frac{2 c r_1 r_2^2}{(ct)^2 - L^2}$$

- **RL**

$$I_{rev}(r_1, r_2) = S \frac{4}{r_1 r_2 H^2} \int_0^{\pi/2} d\theta_1 \int_0^{\pi/2} d\theta_2 \left| R(\theta_1) \right|^{r_1 \tan\theta / H} S(\theta_1, \theta_2, \Theta) A(r_1, r_2, \Theta) \left| R(\theta_2) \right|^{r_2 \tan\theta / H}$$

Reverberation Modeling Approach

- **Use Harrison's formulae inspired by Weston for the rapid estimation of bistatic reverb in iso-velocity range independent environments**

- **TL**

$$I(r_1) = \frac{2}{rH} \int_0^{\pi/2} \left| R(\theta) \right|^{r_1 \tan\theta / H} d\theta$$

- **Area**

$$A(r_1, r_2, \Theta) = \delta t \delta \phi \frac{2 c r_1 r_2^2}{(ct)^2 - L^2}$$

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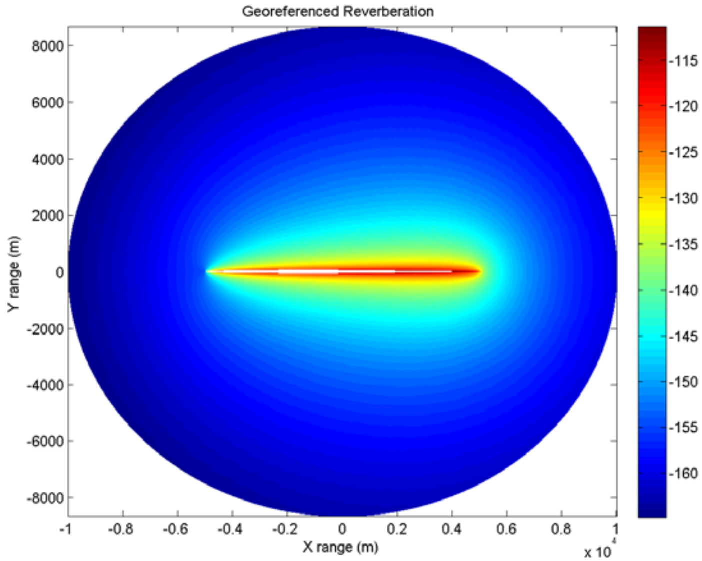
$$I_{rev}(r_1, r_2) = S \frac{4}{r_1 r_2 H^2} \int_0^{\pi/2} d\theta_1 \int_0^{\pi/2} d\theta_2 \left| R(\theta_1) \right|^{r_1 \tan\theta / H} S\left(\theta_1, \theta_2, \Theta\right) A\left(r_1, r_2, \Theta\right) \left| R(\theta_2) \right|^{r_2 \tan\theta / H}$$



SNR Objective Function with BENS Aperture in Possible Receiver Space

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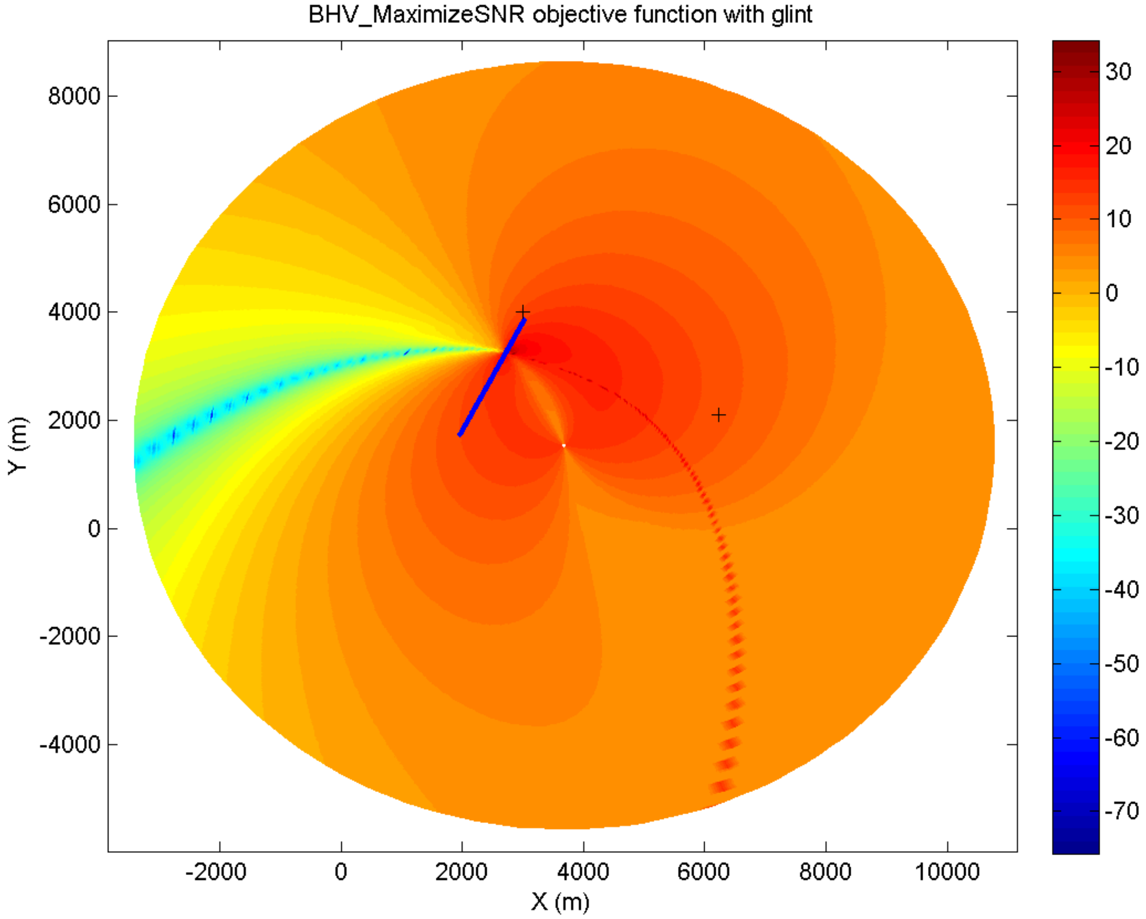

SNR Objective Function with BENS Aperture in Possible Receiver Space

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