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SEGMENTATION OF ROAD EDGES FROM A VEHICLE-MOUNTED IMAGING RADAR

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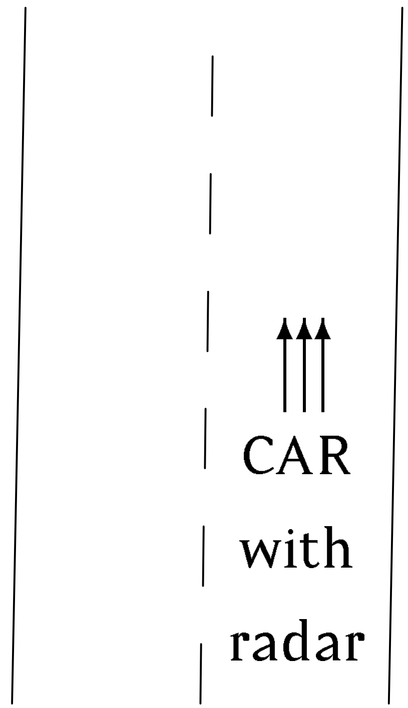
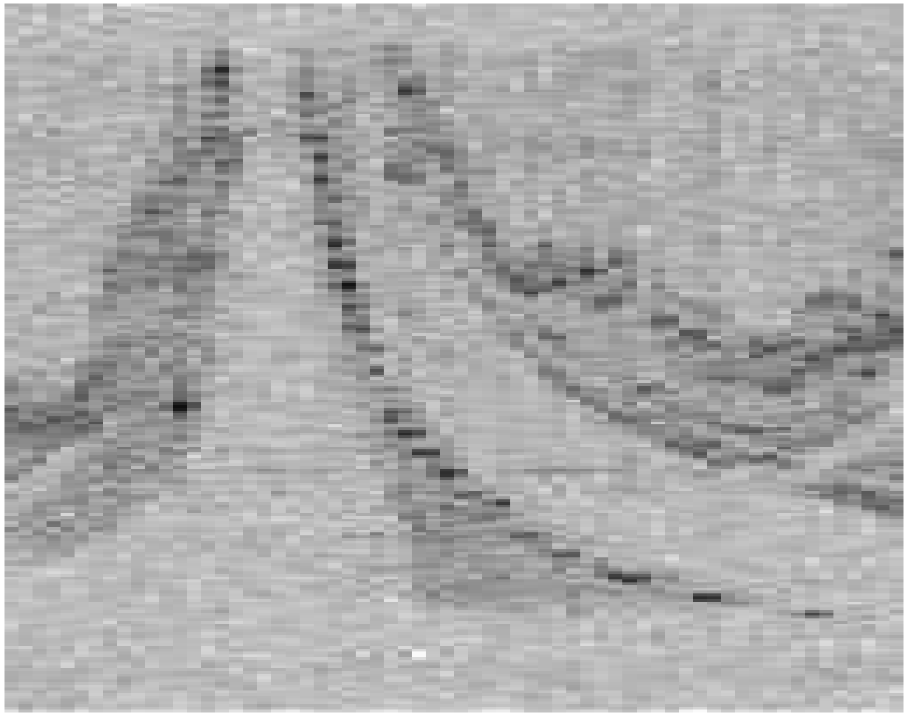
Problem Formulation



(millimeter-wave radar)



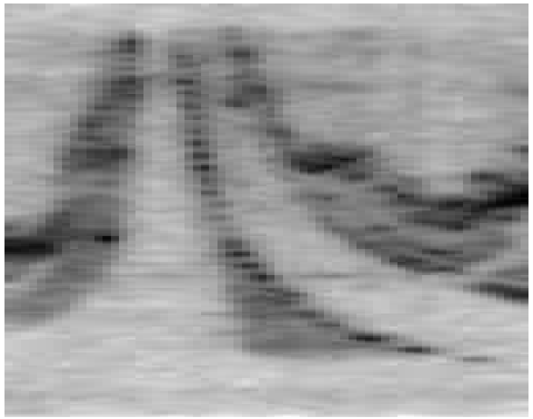
Log-Data (polar coordinates)

Objective: find the edges of the road

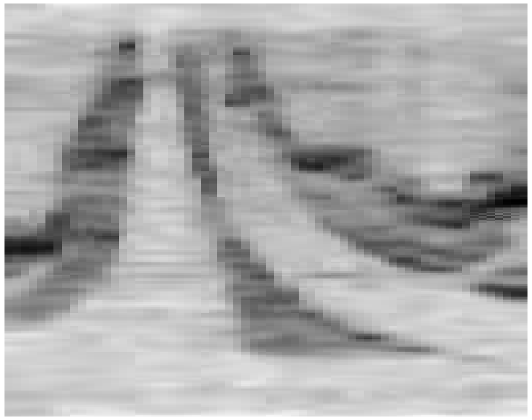
Challenges: **robustness & low computation in high clutter conditions, and changing visibility, road surface variability, cross roads and other vehicles**

- **Data degradation factors:**
  various scatter + clutter sources, 1/R resolution spreading

- **Standard ad hoc techniques are ineffective**



Quadratic regu.



Median filtering

- **Global structure:**

Left offroad	**ROAD**	**Right offroad**

homogeneous, regular shape

⇒ *Global shape models* ⇒ *Deformable template models*

- Constraint of simplicity ⇒ Fast convergence

Parabolic Road Edge Model

- Public roads and highways:
  road edges specified by pair of coupled smooth functions

  Such roadways have minor variations over field of view

$\Rightarrow$ *Road boundaries: curvature & width are constant over field of view*

$\Rightarrow$ **Edges of the road modeled as parabolic curves**
Road is totally homogeneous and is $\neq$ from Offroad

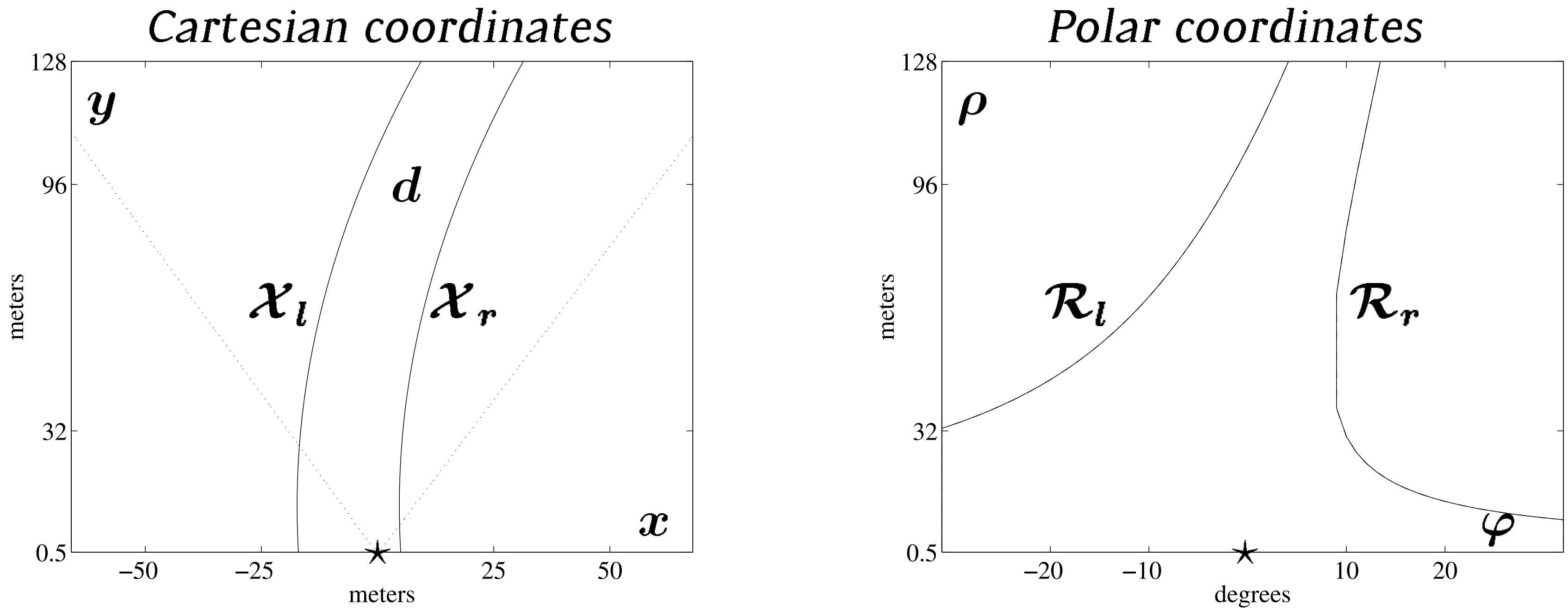
- **Left edge:** $\mathcal{X}_l(y) = ay^2 + by + c_l$ **Right edge:** $\mathcal{X}_r(y) = ay^2 + by + c_r$ (X)

  $d = c_r - c_l$: width of the road

  c_r: distance from the car to the right edge of the road

Road segmentation $\Longleftrightarrow$ **Find** (a, b, c_r, d)

How to Fit Model to Data?



- **Note: Acquired radar image is in polar coordinates $z(\varphi, \rho)$**

  Angular resolution of data $\downarrow\downarrow$ with distance (Res)

  $\Rightarrow$ **high resolution information is in near field**

- **Mismatched data and model Domains**

  An issue: transform z into the (x, y)-domain

  $\Rightarrow$ Difficulty: how to deal with spatially variant data interpolation errors?

- **Solution:**

  Transform the parabolic model into the polar domain
  $\Rightarrow$ estimation directly from recorded data

  $\Rightarrow$ Permits also to exploit (Res)

- **Parabolic curves $\mathcal{X}_{l,r}(y)$ expressed in polar coordinates $\mathcal{R}_{l,r}(\varphi)$:**

$$ac_{l,r} \leq 0 \quad \Rightarrow \quad \mathcal{R}_{l,r}(\varphi) = \frac{-\mathcal{B}(\varphi) \; + \; \mathrm{sign}(a)\,\mathcal{D}(\varphi)}{2a\cos^2(\varphi)}$$

$$ac_{l,r} > 0 \quad \Rightarrow \quad \mathcal{R}_{l,r}(\varphi) = \frac{-\mathcal{B}(\varphi) \; \pm \; \mathcal{D}(\varphi)}{2a\cos^2(\varphi)} \qquad \text{(multivalued function)}$$

where
$$\begin{aligned} \mathcal{B}(\varphi) &= b\cos(\varphi) - \sin(\varphi) \\ \mathcal{D}(\varphi) &= \sqrt{\mathcal{B}^2(\varphi) - 4ac_{l,r}\cos^2(\varphi)} \end{aligned}$$

Discrete Formulation

- Azimuth-range radar data $\{(\varphi_m, \rho_n),\ -M/2+1 \leq m \leq M/2,\ 1 \leq n \leq N\}$

  field of view $|\text{azimuth}| \leq 32^\circ$, range ≤ 128 m $\Rightarrow$ $M = 64,\ N = 256$

- Rebinning $\mathcal{R}_{l,r}$ $\Rightarrow$ $\Phi_{l,r}(\rho_n)$ for fixed range gate ρ_n

- Define road pixels: $\mathcal{S} := \{(n,m)$ such that $\Phi_l(\rho_n) \leq \frac{m\,\pi}{180} \leq \Phi_r(\rho_n)\}$

$\Rightarrow$ **Road pixels are parameterized** $\mathcal{S} = \mathcal{S}(a, b, c_r, d)$

- **Log-normal likelihood function of the radar image**

$$P(z|\mathcal{S}) = \prod_{C \in \{\mathcal{S}, \mathcal{T}_L, \mathcal{T}_R\}} \prod_{(n,m)\in C} \frac{\exp[-\frac{(\log z_{n,m} - \mu_C)^2}{2\sigma_C^2}]}{z_{n,m}\sqrt{2\pi\sigma_C^2}}, \qquad y_{n,m} := \log z_{n,m} \qquad \text{(LH)}$$

- **Assumption for** (LH): *offroad backscatters* $\mathcal{T}_L, \mathcal{T}_R$ *are homogeneous* (Sim)

Details of Segmentation Algorithm

Step 1: Make coarse estimate of road width $\widehat{d}$

- (Res) $\Rightarrow$ **Estimate $\widehat{d}$ from the first L meters in front of the car** ($L \approx 30$–40)

1.1: **Rough estimation of $\widehat{d}$:** **Linearly approximate the road edges over L**

$\Rightarrow$ $a = 0$ in (X),(R) $\Rightarrow$ $\mathcal{S} = \mathcal{S}(0, b, c_r, d)$

$\Rightarrow$ **Linear edges in polar coordinates simpler than quadratic edges**

$$\tilde{\mathcal{R}}_{l,r} = \frac{c_{l,r}}{\sin\varphi - b\cos\varphi}, \quad \tilde{\Phi}_{l,r} = \frac{-\rho + \sqrt{(1+b^2)\rho^2 - c_{l,r}^2}}{b\rho - c_{l,r}} \tag{RL}$$

- **Estimator based on** (LH): $(\widehat{b}, \widehat{c}_r, \widehat{d}_{rough}) = \arg\max P(z|\mathcal{S}(0, b, c_r, d))$

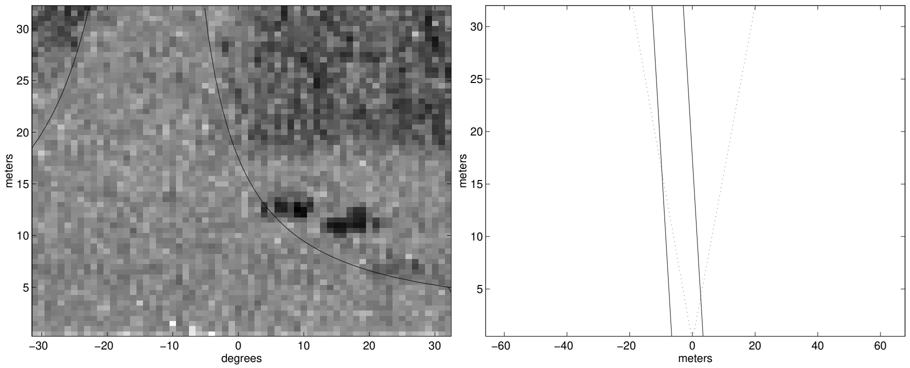
- **Reduced numerical complexity**

  (only 3 parameters, expressions (RL) are simple, only a L-portion of z is processed)

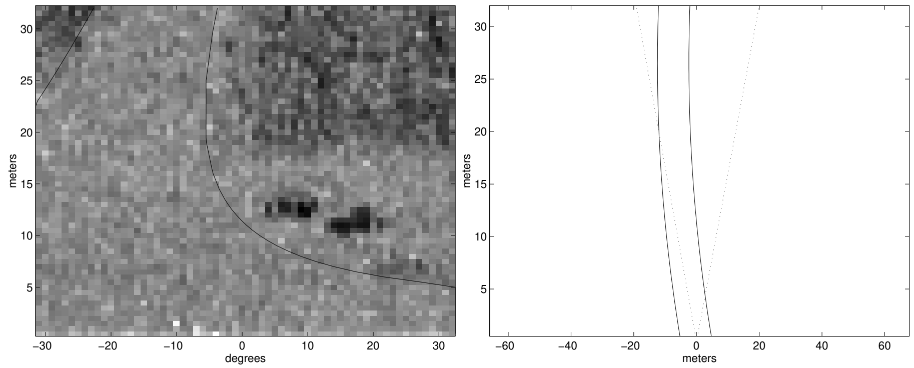
1.2: Refinement of $\widehat{d}$ obtained in *1.1*: Parabolic model over L

- **Estimator:** $\widehat{d} = \arg\max_{d \in \mathcal{V}(\widehat{d}_{rough})} \max_{a,b,c_r} P(z|\mathcal{S}(a,b,c_r,d))$,

  (The L-portion is insufficient to reliably evaluate $a,\ b,\ c_r$)



Rough estimate from L=32 m, $\widehat{d}_{rgh}$=10 m.



Refined estimate, $\widehat{d} = 10$ m.

Accurate estimation of $\widehat{d}$ is crucial for the sequel!

Robustification of estimator to offroad backscatters

- (Sim) **is unrealistic: No assumption can be formulated for the offroad!** (OR)

Estimator = Find over the image (in cartesian coordinates) **the patch of width $\widehat{d}$ which is the most homogeneous**

- **Criterion involving only the pixels of the road**

$$\mathcal{J}(a, b, c_r; \widehat{d}, y) = \frac{1}{\#\{\mathcal{S}(a, b, c_r, \widehat{d})\}} \sum_{(n,m)\in\mathcal{S}(.)} (y_{n,m} - \widehat{\mu}_{\mathcal{S}(.)})^2$$

$$\widehat{\mu}_{\mathcal{S}(.)} = \frac{1}{\#\{\mathcal{S}(.)\}} \sum_{(n,m)\in\mathcal{S}(.)} y_{n,m}$$

$\Rightarrow$ **Estimator:** $(\widehat{a}, \widehat{b}, \widehat{c}_r) = \arg\min_{a,b,c_r} \mathcal{J}(a, b, c_r\ ;\ \widehat{d}, y)$ (Est)

- **Important advantages**
  - *Side regions $\mathcal{T}_L$ and $\mathcal{T}_R$ do not affect optimization*
  - *Assumptions about $\mathcal{T}_L$, $\mathcal{T}_R$ reduced to a minimum* $\Rightarrow$ (OR) *respected*

Step 2: **Find ROI containing the road**

- **Piecewise linear segmentation of the road**

- **The image is partitioned into several (eg., 4) horizontal sections**

- **A linear model** (RL) **formulated in each section**

  $\Rightarrow \quad \boldsymbol{a} = \mathbf{0}$ in (X), (R) $\quad \Rightarrow \quad$ simple model equations of the form (RL)

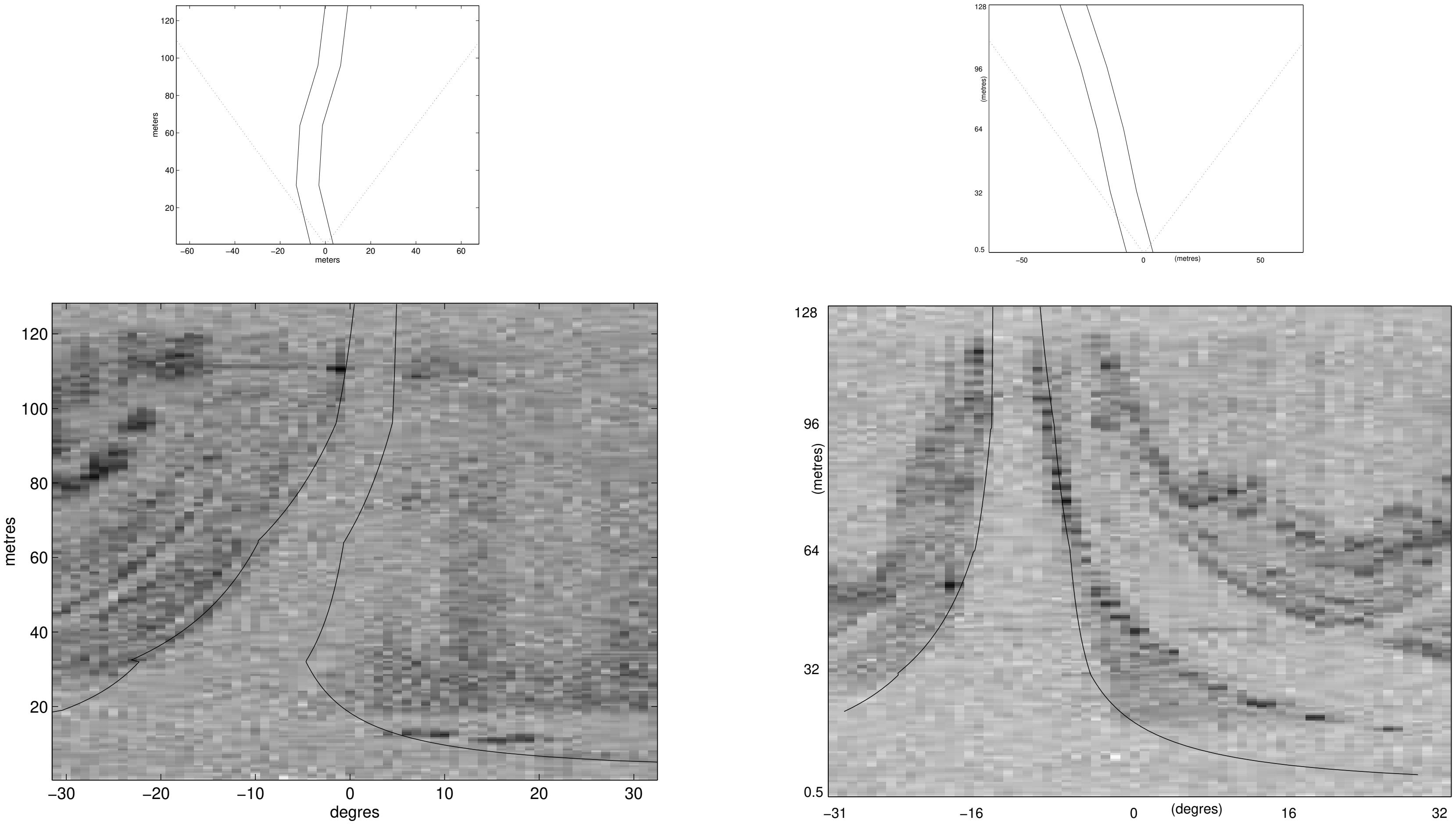
- **Parameters to estimate** $=$ (**number of sections** $+1$)

  - First section: $\boldsymbol{b}^{(1)},\ \boldsymbol{c}_{\boldsymbol{r}}^{(1)}$

  - Next sections ($\boldsymbol{k} \geq \mathbf{2}$): only $\boldsymbol{b}^{(\boldsymbol{k})}$

    [$\boldsymbol{c}_{\boldsymbol{r}}^{(\boldsymbol{k})}$ specified by ($\boldsymbol{b}^{(\boldsymbol{k}-1)},\ \boldsymbol{c}_{\boldsymbol{r}}^{(\boldsymbol{k}-1)}$) satisfying continuous road constraint]

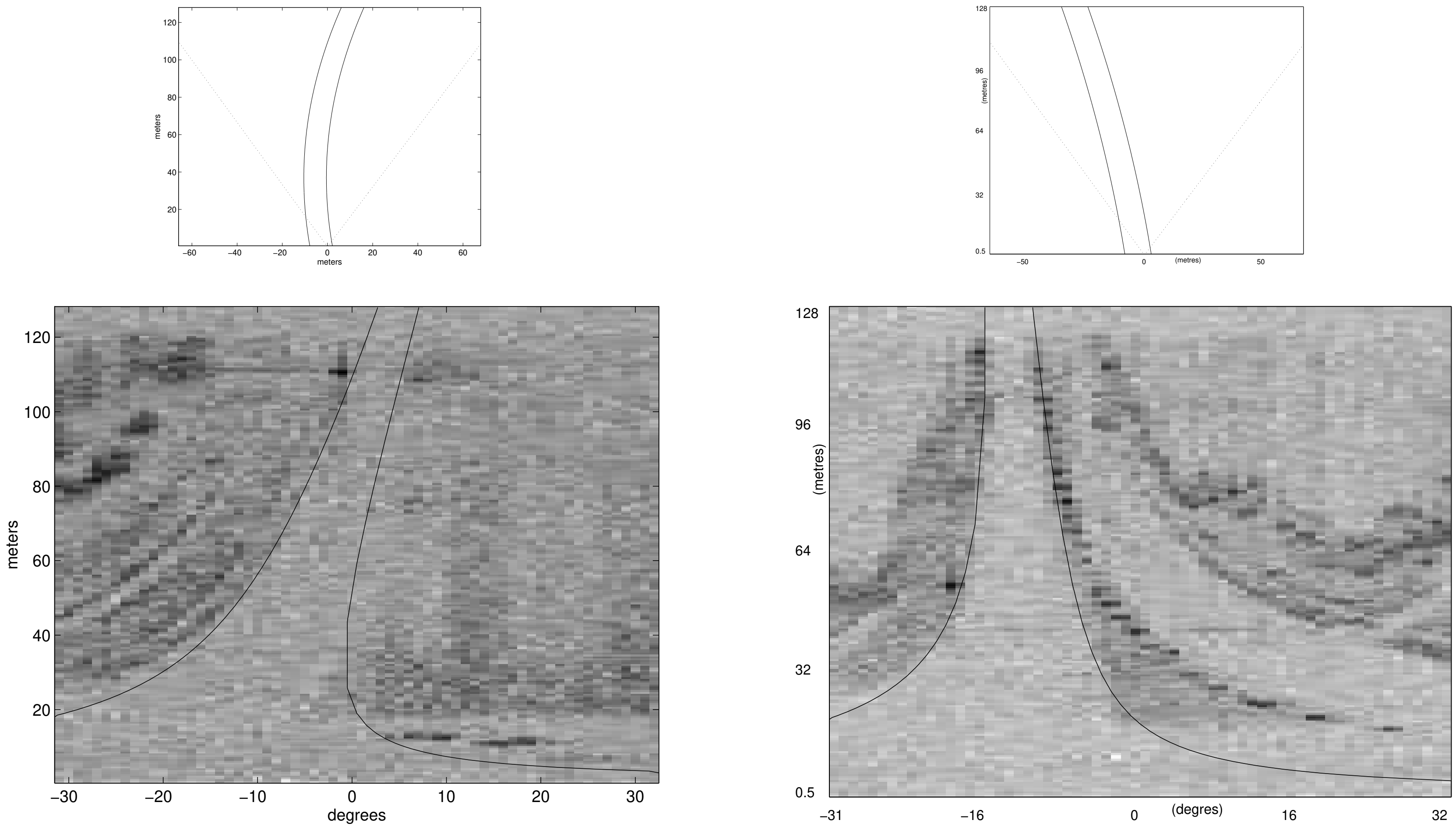
⇒ Rapid coarse segmentation of the road



- Road edges have sharp corners
- *Faithfull location of the region of the road* ⇒ *ROI* (ROI)

Step 3: Fine segmentation using parabolic model (R)

- **Feasibility domain:** $\mathcal{D} = \{(a, b, c_r)$ such that $\mathcal{X}_{l,r}(a, b, c_r) \in \text{ROI}\}$ (D)
- **Estimation using** (Est) **subject to** $(a, b, c_r) \in \mathcal{D}$



Optimization Methodology

Criterion $\mathcal{J}$ is nonconvex with respect to (a, b, c_r, d)

- *Variation of criteria with respect to parameters is very smooth*
  (minima are not "too narrow")

- **Strategy:** *Enforce reliable feasibility domains*
  (other constraints can be formulated, in addition to (D))

⇒ **An approach:** **Pseudo-exhaustive hill climbing optimization**

  Parameters are finely sampled over $\mathcal{D}$
  $\mathcal{J}$ is evaluated for all parameter samples
  The resultant values of $\mathcal{J}$ are compared

- Observation: Piecewise linear models are not very sensitive to sampling resolution

Conclusions and Future Work

- **Recent experiments**
  - If road "too large" $\Rightarrow$ left edge "too far away" $\Rightarrow$ $\widehat{d}$ inaccurate
    Solution: increase L in Step 1
  - Car on a sharp turn $\Rightarrow$ linear model in *1.1* inaccurate $\Rightarrow$ $\widehat{d}$ underestimated
    Solution: use piecewise linear model over the L-portion + decimation
- **Issues to study and further improvements**
  - Examine and improve the constraint sets
  - Find an "optimal" parameter sampling over $\mathcal{D}$
  - Automatically determine a pertinent L-zone for the estimation of d
  - Use full video sequence (2 f/sec) $\Rightarrow$ track parameters via local updating

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