FFI Forsvarets forskningsinstitutt

Terrain Navigation
Principles and Application

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Geodesi og hydrografidagene

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Background and History

- TERCOM conceived by *Chance-Vought* in 1958
  - Later and still applied to cruise missiles (e.g. Tomahawk)

- A Kalman filter based system suggested by *Hostetler* in 1976, developed into SITAN by Sandia National Laboratories
  - AFTI/SITAN: F16 terrain navigation 1985
  - HELI/SITAN: helicopter terrain navigation 1990

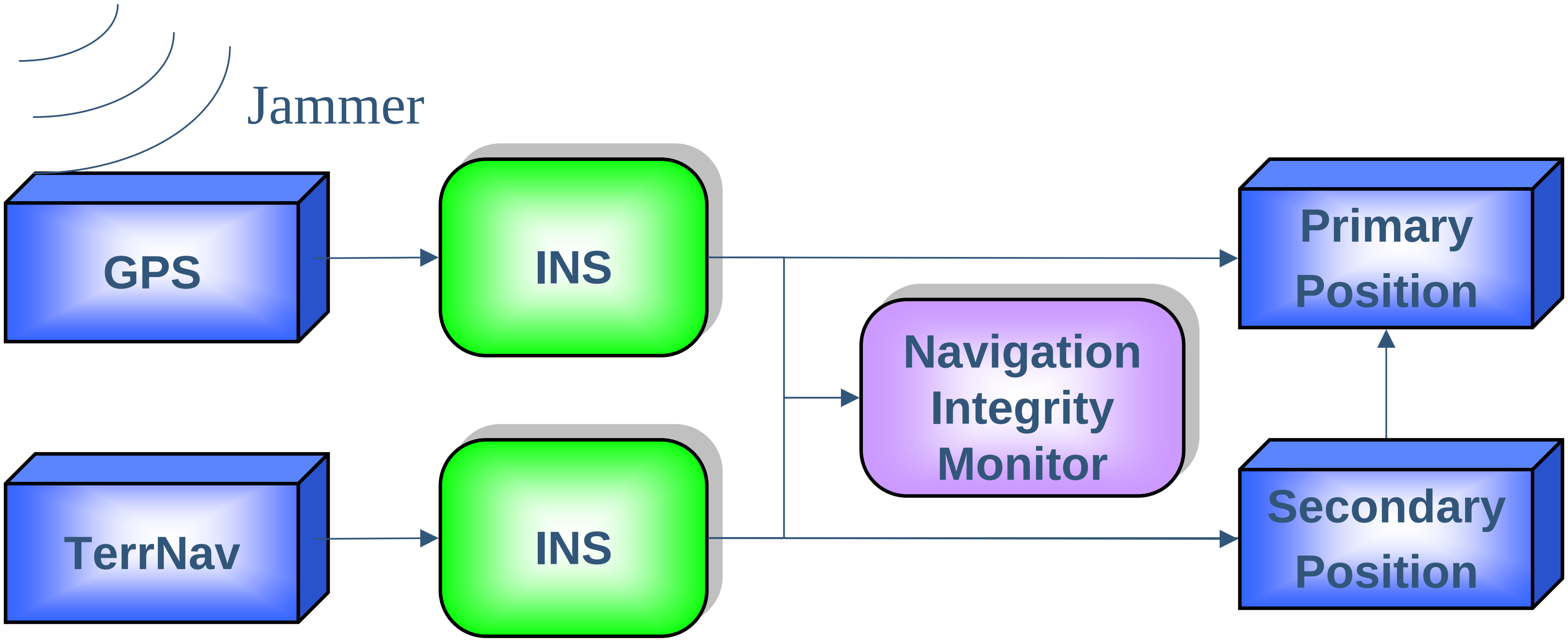
- TERPROM a fusion of TERCOM (initial mode) and SITAN (track mode) developed by BAE systems during the 80s

- FFI generalisation of SITAN algorithm for bathymetric navigation (developed independently) in 1997 by *Heyerdahl* and *Kloster*
  - Developed into TRIN: AUV terrain navigation with DVL in 2001

- Non-linear Bayesian approach by *Bergman* in 1999 for aircraft terrain navigation (SAAB)
  - Point mass filter (PMF) and particle filters

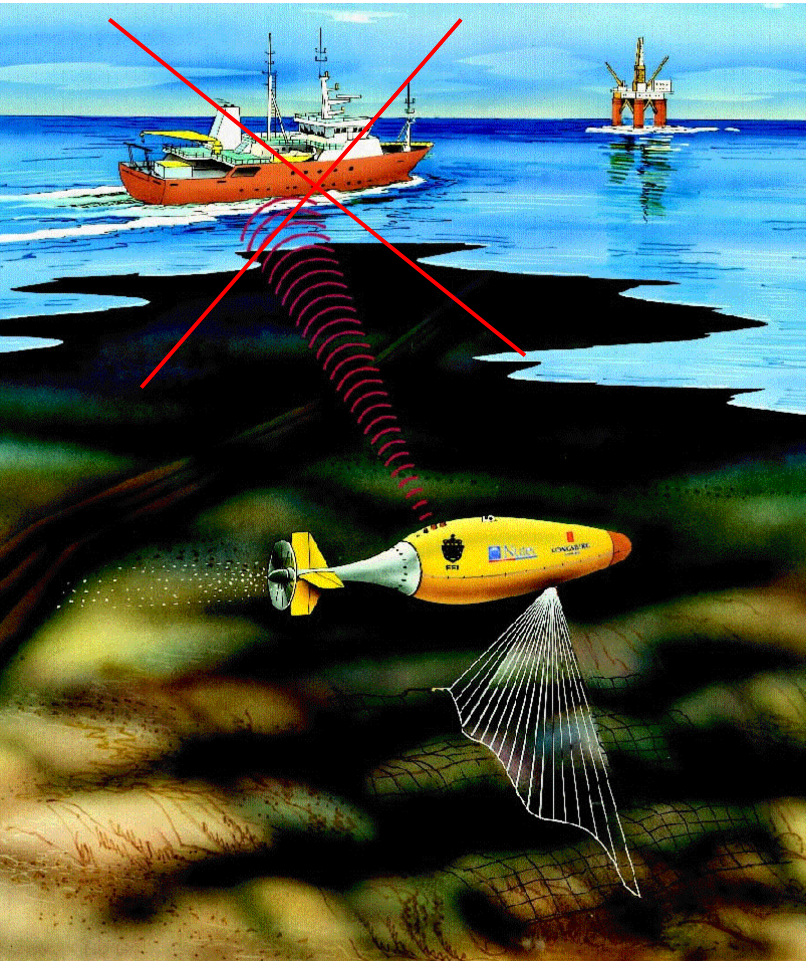
Why use Terrain Navigation?

- Surface and Air applications: GPS is available
  - Redundant navigation system in critical systems
  - Navigation system integrity
  - Backup navigation system during GPS fall-outs or jamming



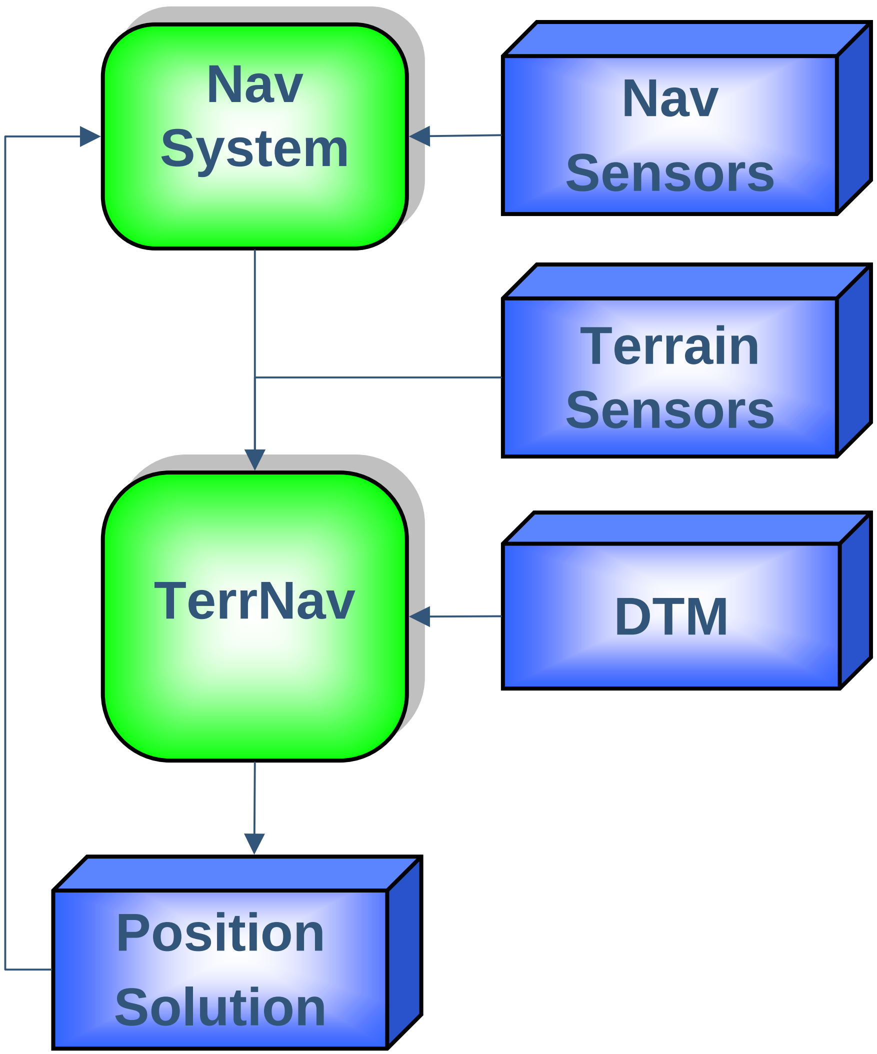
Why use Terrain Navigation?

- Underwater applications:



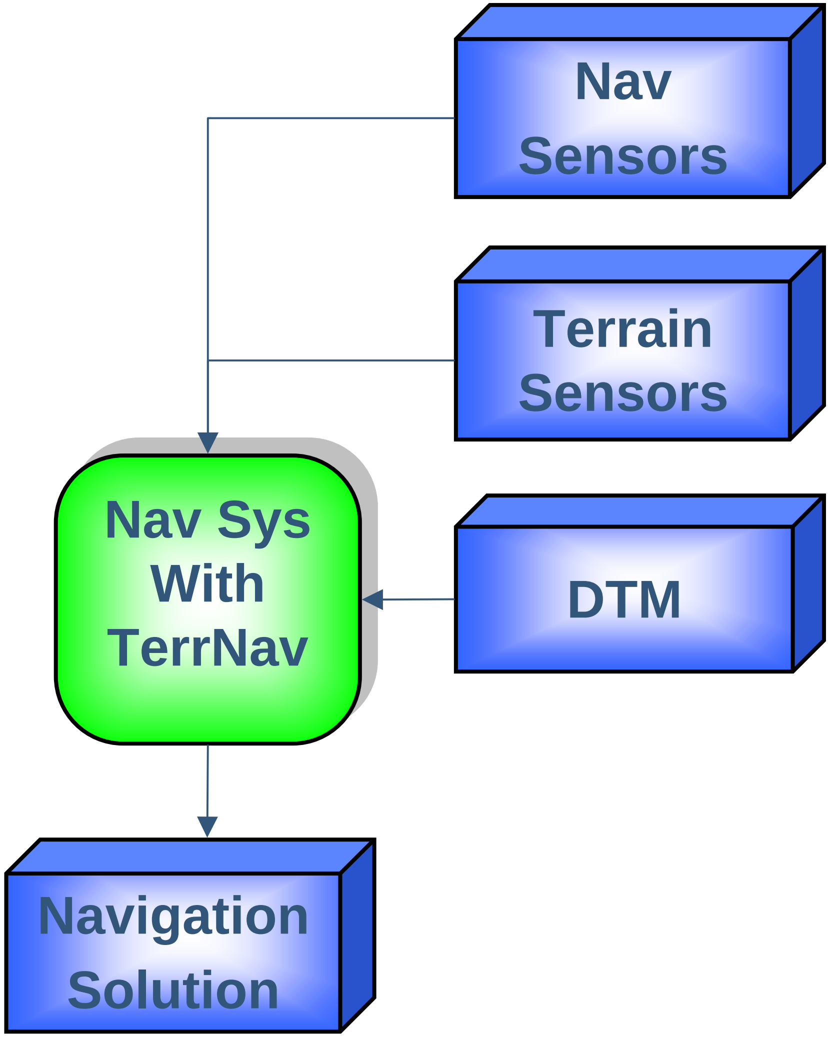
  - GPS is not available
  - Deepwater: GPS fix not feasible
  - Shallow water: GPS fix possible
    - Not in covert operations
  - No infrastructure required
    - DGPS-USBL requires a mother ship
    - LBL / UTP requires transponder(s)

Basic Principles



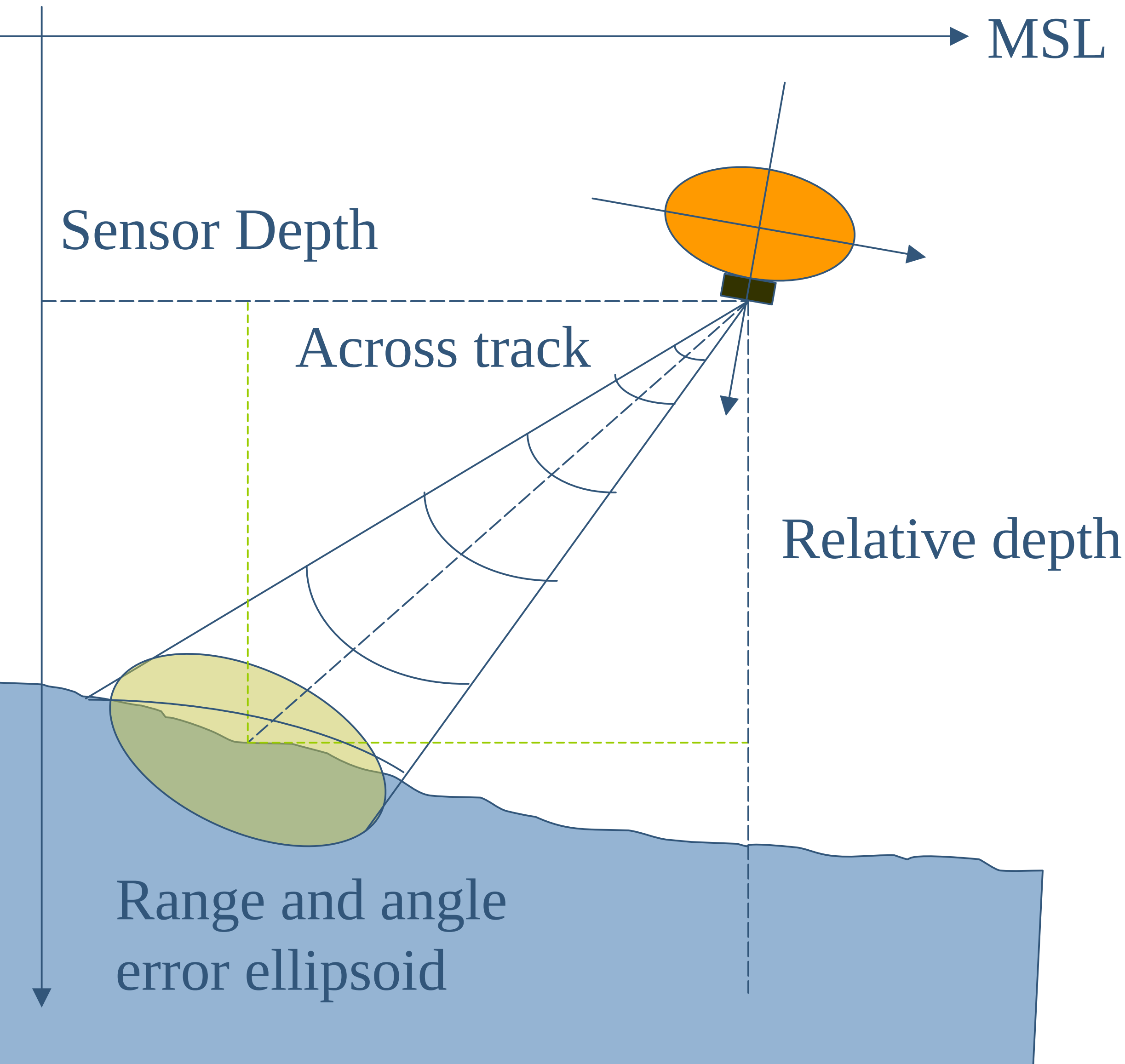
- Lose integration
  - Navigation system data are combined with terrain measurements
  - Correlated with the expected DTM value in a search area
  - A Position solution is produced and passed back to the Navigation System
- Algorithms:
  - TERCOM
  - Point Mass Filter
  - Particle Filters
- Usually batch within ping
  - Batch over time interval possible
  - Recursive possible

Basic Principles



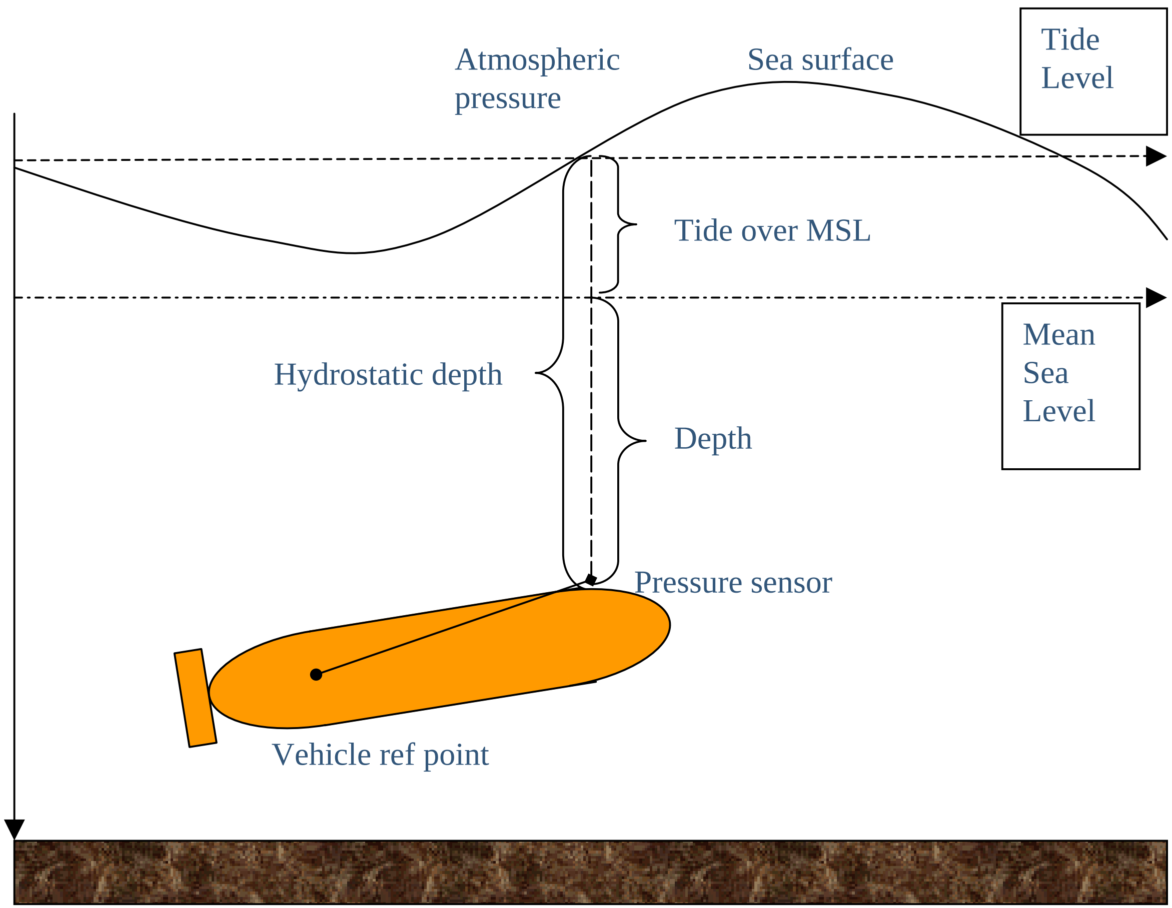
- Tight integration
  - Terrain sensors are integrated along with Nav sensors
  - Correlated with the expected DTM value of current navigation solution
  - Full navigation solution is produced
- Algorithms
  - Kalman filter based
  - TRIN
  - SITAN
- Always recursive in time
  - Batch within ping possible

Underwater Measurement Geometry



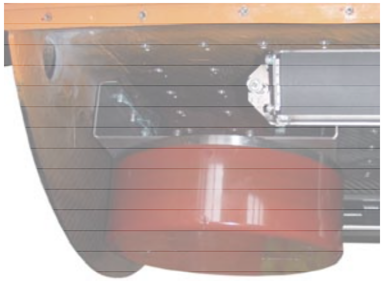
- Sensor ensonifies a seafloor area
  - The footprint
- Slant range and angles are computed
  - Ray bending
  - The beam vector
- The beam vector is transformed into a body-fixed earth tangent plane system
  - Relative depth
- Further transformed into a Global Reference System
  - Global depth

Underwater Vertical Reference



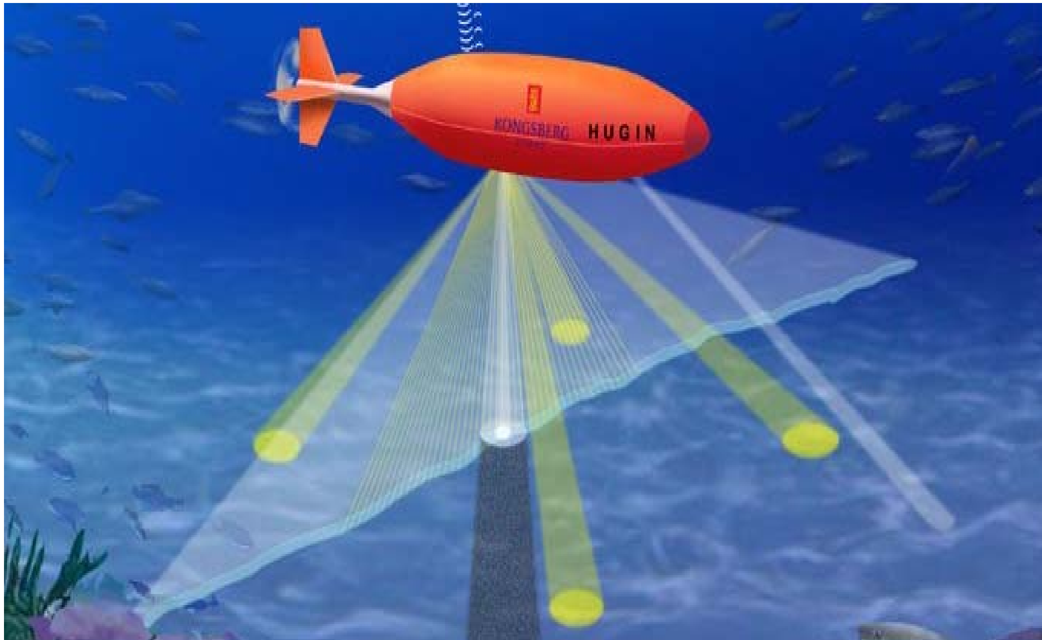
- The vehicle measures pressure
- Vertical reference error directly adds to seafloor depth estimate error
  - Correlated between each beam
  - Correlated in time
- Slow-changing bias is ok
  - Tidal wave error
  - Atmospheric pressure error
  - CTD error
- Dynamic pressure error is not ok
  - Waves

Bathymetric sensors

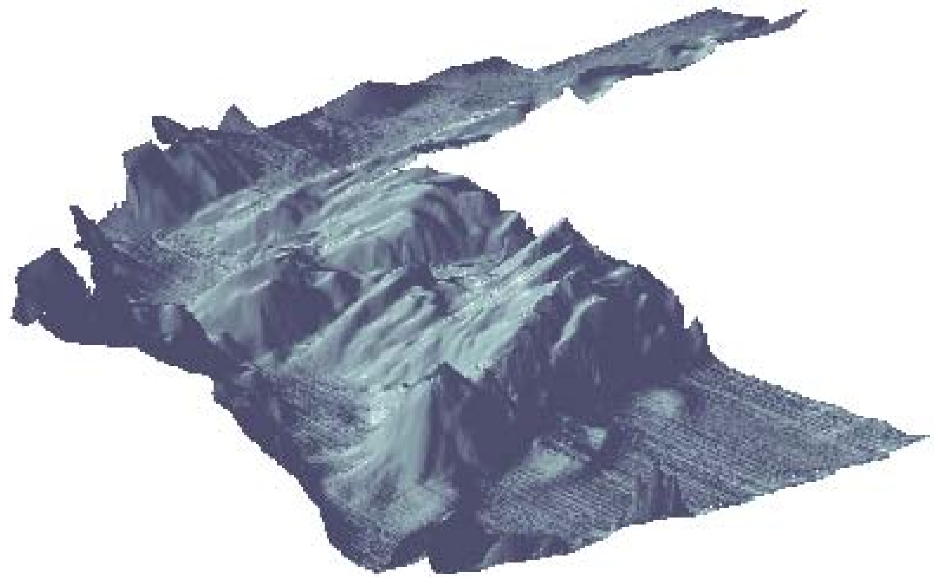


- Multibeam Echosounder (MBE)
  - Across track profile at each ping, a fan of beamvectors
  - EM3000 tested from surface ship and Hugin AUVs
- Doppler Velocity Log (DVL)
  - 4 beamvectors in Janus configuration
  - RDI WHN 300,600,1200 tested on AUVs (Hugin, OEx, Remus)

- Single Beam Echosounder
  - Large footprint
- Interferometric SAS
  - High resolution
- Underwater Laser Camera
  - High accuracy, low range
- 3D Sonar
  - Surface at each ping



Digital Terrain Models



- Algorithm requirements
  - Random access
  - Fast access
- In memory representation
  - Regular grid
  - Bilinear interpolation
- Resolution requirement
  - Terrain navigation accuracy is in the order of DTM resolution
  - For typical AUV operations: at least 10 m
- Accuracy description requirement
  - Ideally a spatial statistical description (grid node depth error)
  - Usually not available in exchanged DTMs

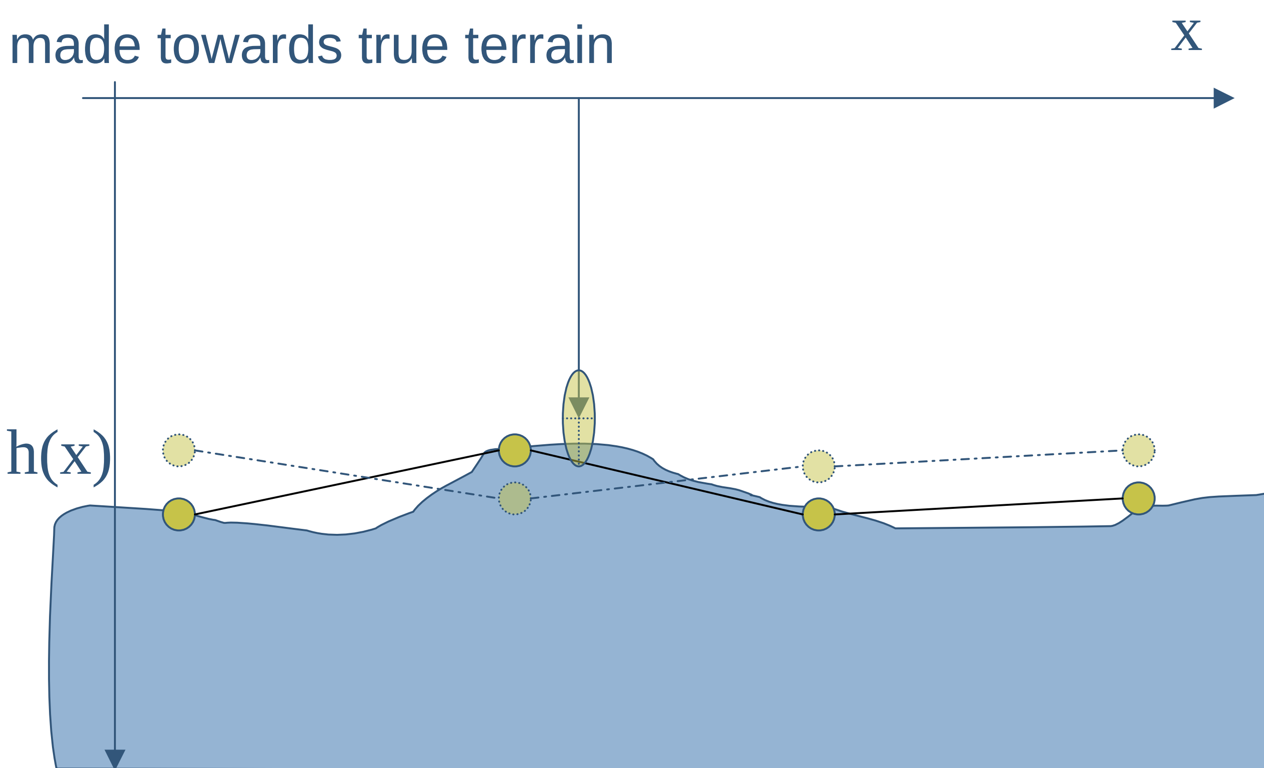
Sensor/DTM measurement model

- We only have a model of true terrain h(x)
  - Horizontal node spacing
  - Interpolation
  - Node depth estimates

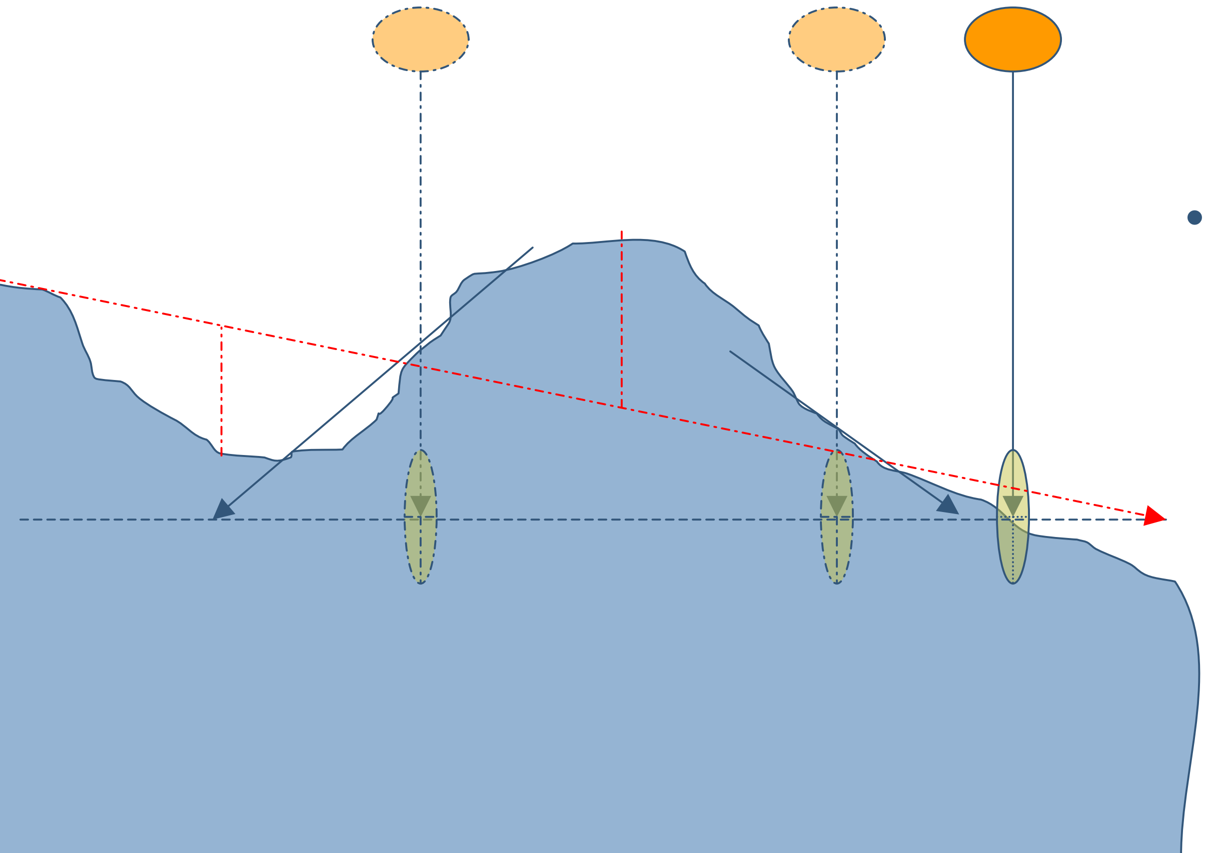
Deterministic

Stochastic

- Measurements are made towards true terrain

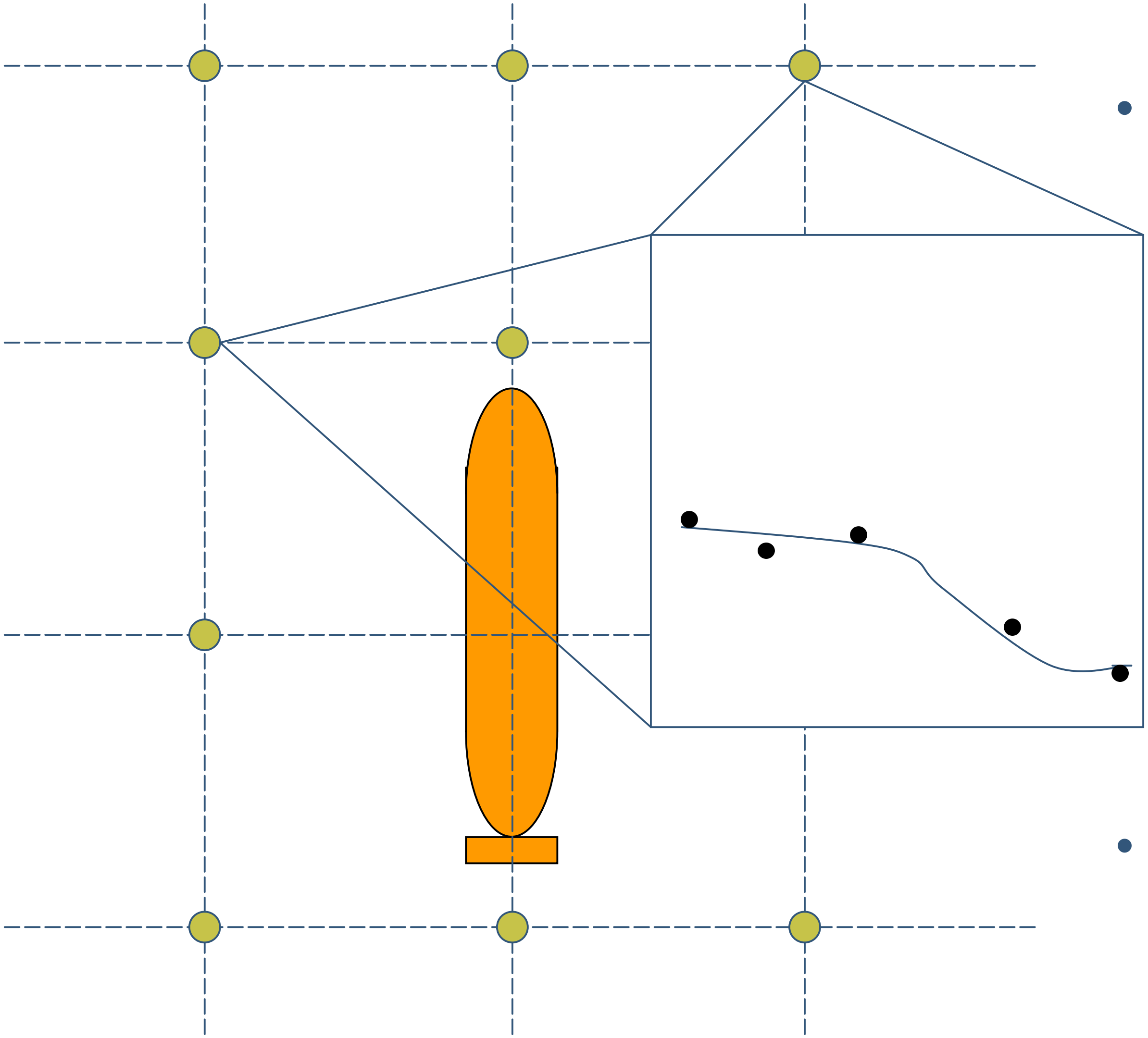


Extended Kalman Filter (EKF) approach (TRIN, SITAN)



- Linearization for EKF requires gradient map
  - Ok in linear and weekly non-linear topography
- Highly non-linear topography handled by stochastic linearization
  - Best fit surface tangent plane within uncertainty area
  - Automatically detects non suitable terrain

Terrain Contour Matching (TERCOM)



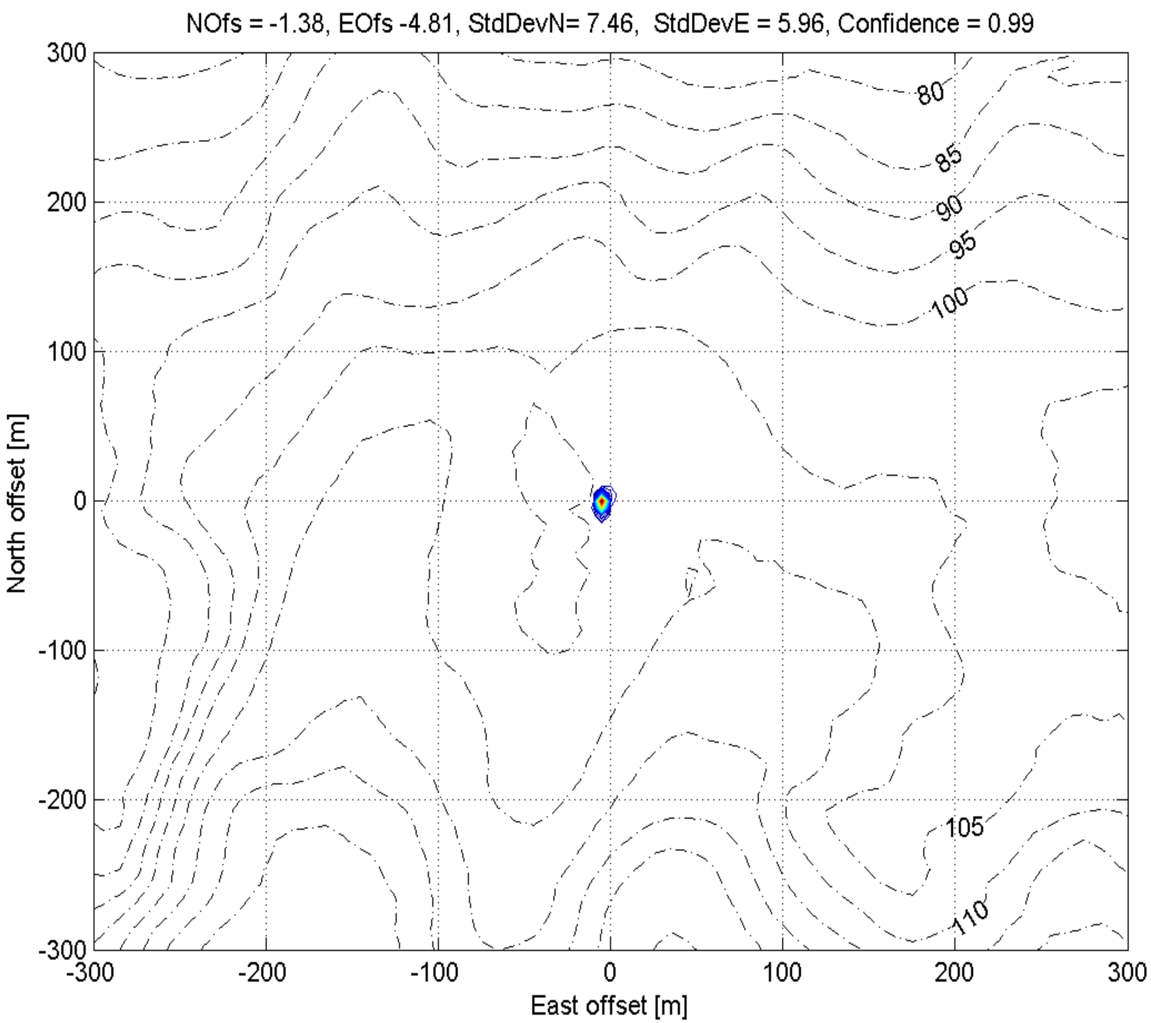
- For each grid point:
  - Calculate mean absolute distance (MAD) between measured and expected profile

Position fix from minimum of the MAD correlation matrix

- No inherent accuracy of fix is available

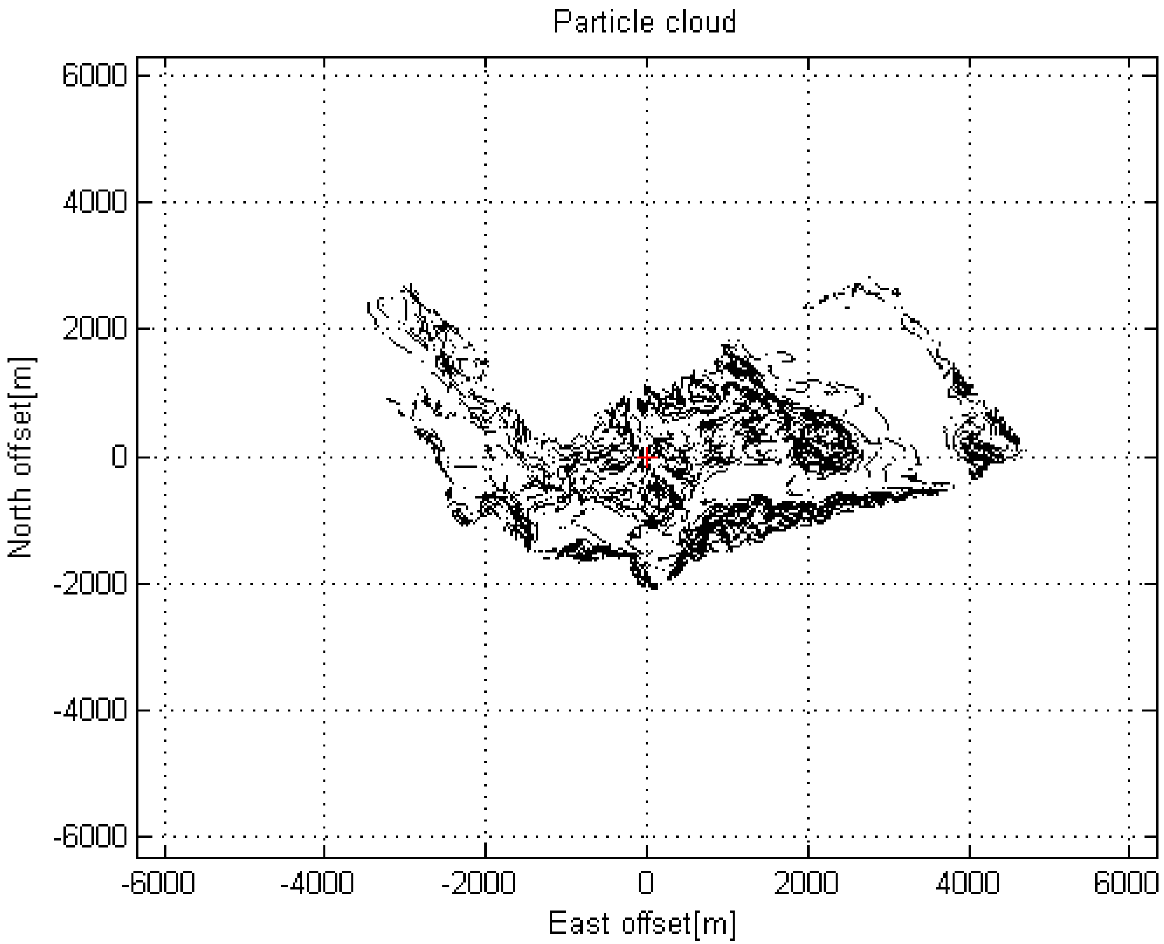
Point Mass Filter (PMF) from TerrP

Ping 8



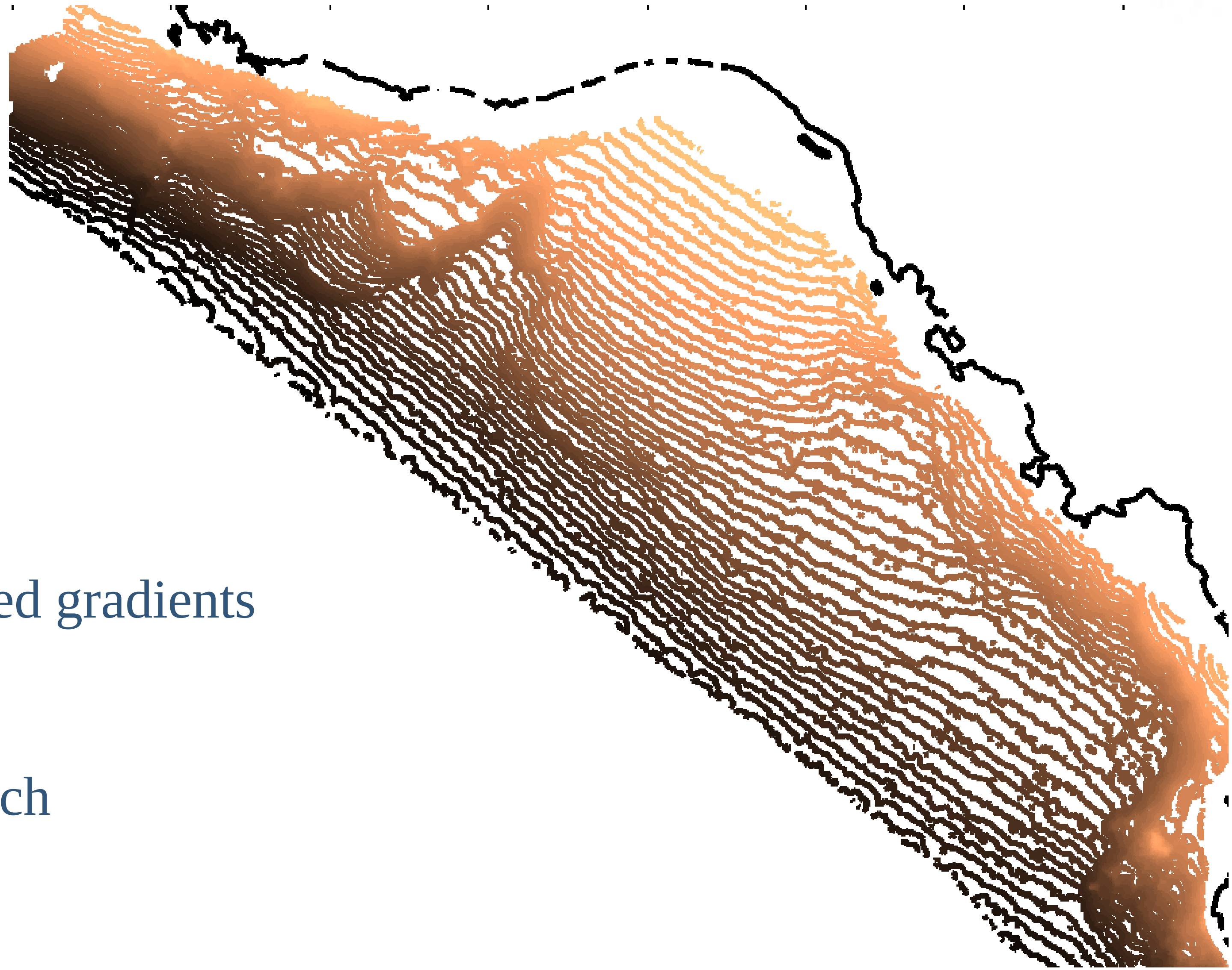
- The position error probability density function (pdf) is estimated on a grid
- An initial pdf, depending on INS accuracy, can be used
- Each measurement is blended with current pdf using Bayes' rule, and a sensor error pdf
- INS drift diffuses the pdf between each ping

Particle Filters (PF) from TerrLab



- Position error pdf represented by free particles
- Initial state is simulated from INS position error distribution
- Measurement: Each particle is weighted using the sensor error pdf
- Resampling
- Dynamic update through simulation on INS drift distribution

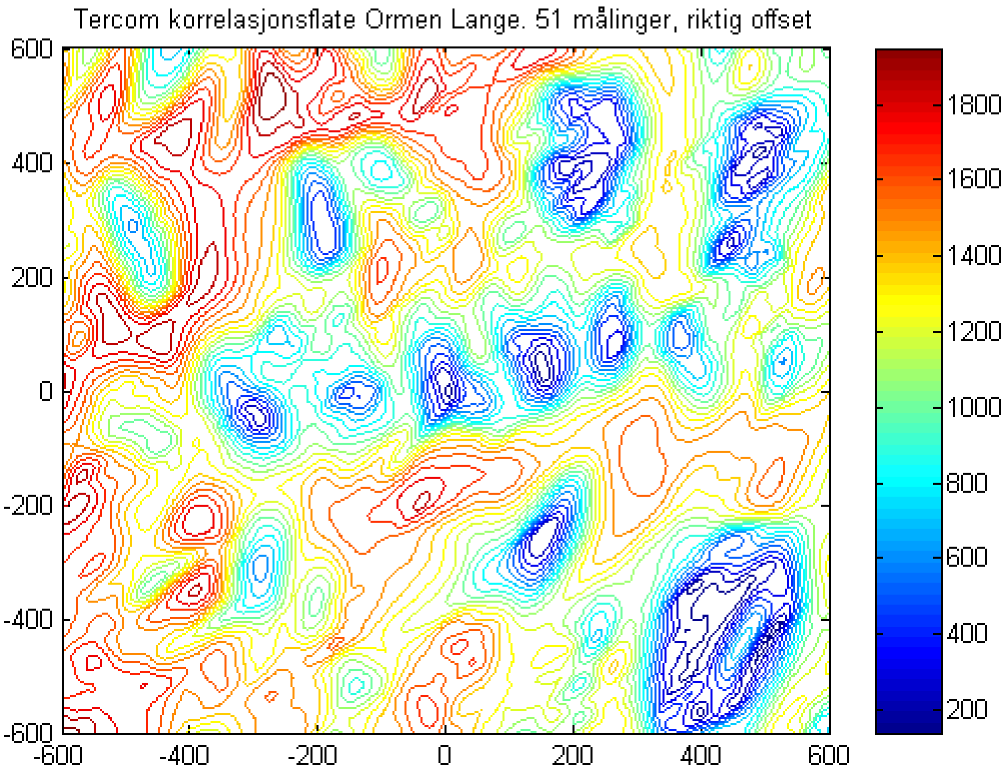
Terrain Suitability?



TRIN, SITAN

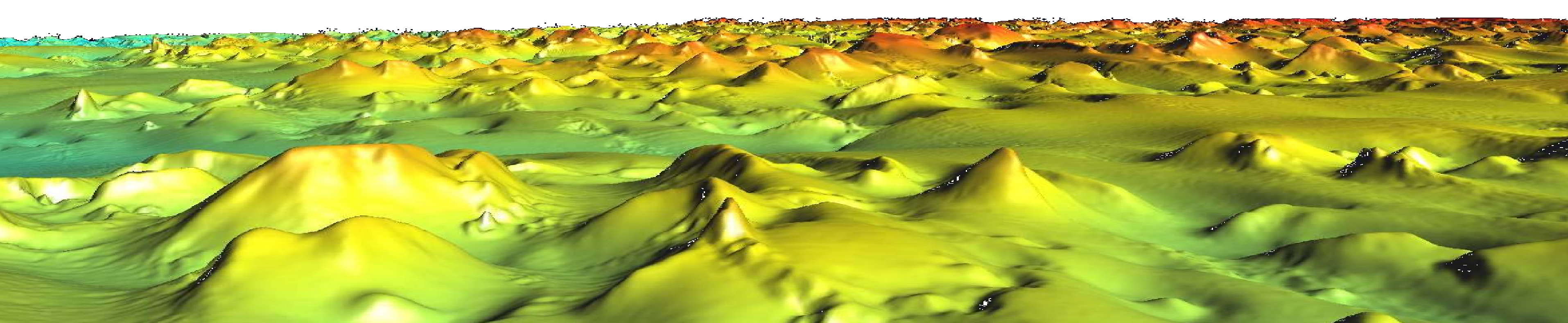
- Clearly defined gradients
- Linear beach
- Parabolic beach
- Fjord

Terrain Suitability?

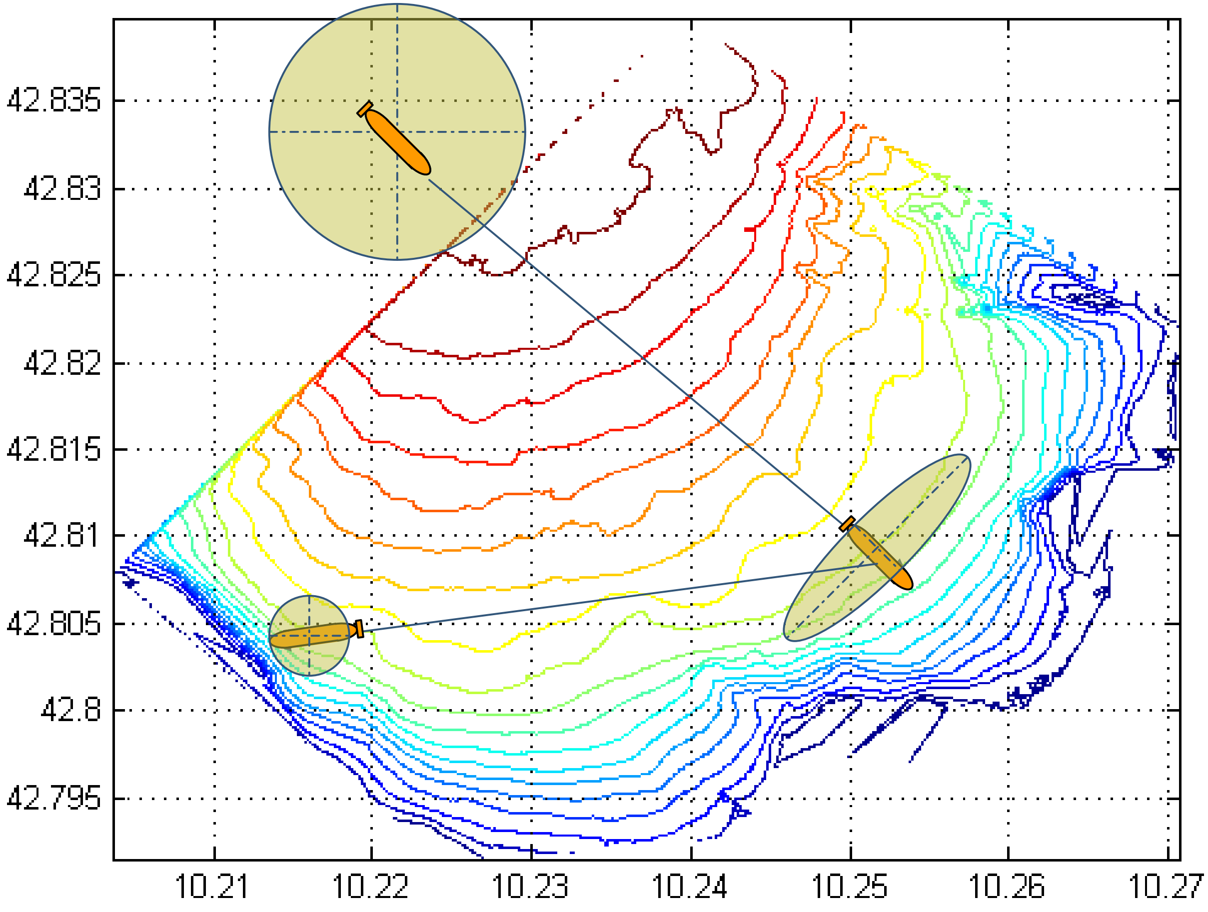


TERCOM, PMF, PF

- Rough topography
- Not self similar



Tactical Use of Terrain Navigation



Applications

- Cruise missiles
  - Backup system
  - Independent of GPS, cannot be jammed
- Fighter aircrafts
  - Redundant navigation system
  - Terrain following aid for low altitude flying
- AUVs
  - Autonomous missions
  - Covert operations
- Submarines
  - Always covert
  - Transmission of sound is restricted
  - “Man in the loop”

FFI Developed Systems

- Terrain Referenced Integrated Navigation (TRIN)
  - MatLab implementation of FFI's EKF based algorithm
  - Verified in 2 NATO experiments for different AUVs and a surface vessel
- Terrain Navigation Processor (TerrP)
  - Real-time terrain navigation system (TERCOM, PMF)
  - Primarily designed for HUGIN
  - Verified on playback of real data from HUGIN
- Terrain Navigation Laboratory (TerrLab)
  - MatLab toolkit for terrain navigation algorithm development, simulation and post processing
  - TERCOM, PMF, Particle Filters