

Performance Measures for Intelligent Systems

From Theory to Experiment

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History

PerMIS'00 -- definition of intelligence

PerMIS'01 -- metrics and measures of intelligence

PerMIS'02 -- methods to perform measurements

PerMIS'03 -- large experiments, data collection

FY03 Major Experiments

ARL/GDRS - Demo III TRL-6 experiments

NIST - TRL-6 terrain characterization data collection

DARPA - PerceptOR off-road perception experiments

DARPA - MARS Urban Search and Rescue Arenas

Boeing/FCS - Integrated Combat Demonstration

FY03 Data Collection

Terrain Characterization Data

High resolution LADAR for geometry

High performance INS/GPS for position

Instrumented trailer for soil mechanics

Woods and fields, desert terrain, snow, urban

Roads and traffic

NIST campus

TRL-6 Experiments

Nov'02 - Fort Indiantown Gap – Woods and fields

Dec'02 - Tooele Army Depot – Desert sagebrush

Jan'03 – Fort Indiantown Gap – Woods, trails, snow

Apr'03 - Fort Indiantown Gap – Urban environment

Total of 550 km distance traversed

Over 90% autonomous operation (distance, time)

Quantitative measures of operator interventions





**GENERAL
DYNAMICS**
Robotic Systems

TRL-6 Experiments + FCS Integrated Combat Demo



**Robotics Technology
TRL6
2002 - 2003**





PerceptOR

Off-Road Perception



Team Raptor



Team Blitz



PerceptOR Goals



- **Apply perception systems to dense obstacle environments**
- **Minimal sensor development (off the shelf)**
- **Develop algorithms while testing in the field**



PerceptOR Status

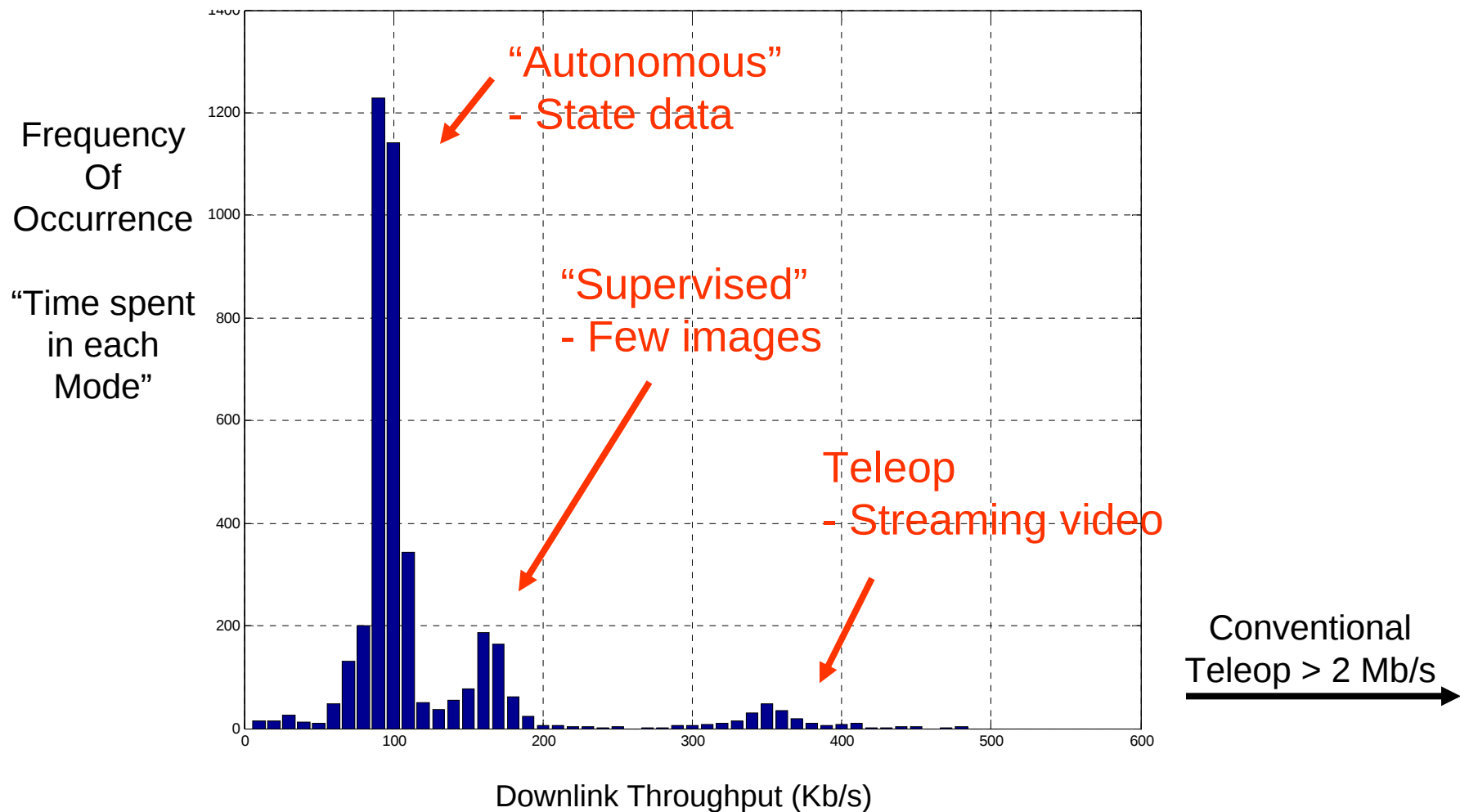


- **Phase II concluded – DEC 02**
 - Four field tests in 2002
- **Phase III initiated**
 - Focus on Technical Thrusts
 - Two Performers
 - Team Blitz – CMU Prime
 - Team Raptor – SAIC Prime
 - (2) Contract tests at their facility in 1st half of 2003
 - (2) Government tests in 2nd half of CY 2003



PerceptOR

Ph II Communications





DARPA MARS



Urban Search & Rescue Testbed

- **3 Robotic USAR Competitions**
 - RoboCup 2003, Rome, Italy
 - IJCAI 2003, Acapulco, Mexico
 - U. S. RoboCup Rescue Open 2003, CMU
- **Scored competitions**
- **Analysis of system performance**





IJCAI/AAAI ARENAS (MEXICO, 2003)



YELLOW ARENA



ORANGE ARENA

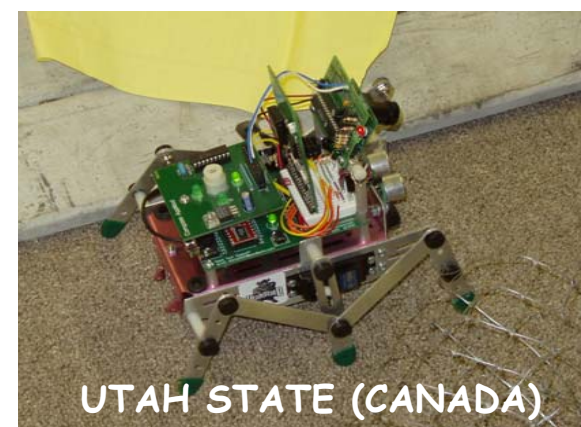


RED ARENA





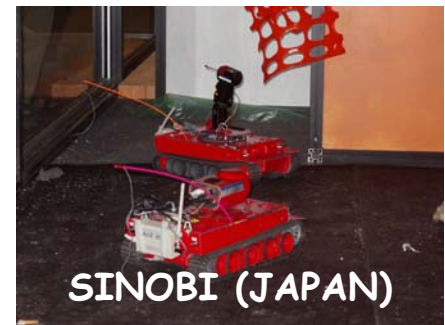
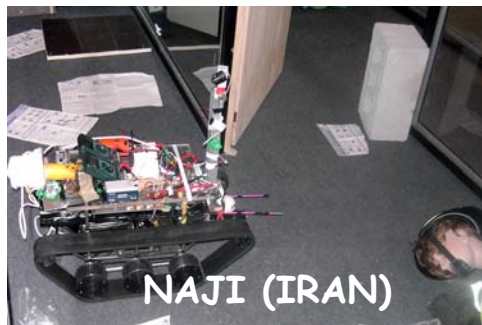
IJCAI/AAAI ROBOTS (MEXICO, 2003)





ROBOCUP ROBOTS

(ITALY, 2003)





USAR ROBOT PERFORMANCE METRIC

$$\text{ARENA WEIGHTING} \left[\frac{\begin{array}{c} \text{50 POINTS POSSIBLE PER VICTIM FOUND} \\ \text{MAP QUALITY} + \text{VICTIM LOCATION} + \text{VICTIM SITUATION} + \text{VICTIM STATE} + \text{VICTIM TAG} \\ \text{PENALTIES PER EVENT} \\ - \text{ARENA BUMPING} - \text{VICTIM BUMPING} \end{array}}{\left[1 + \text{NUMBER OF OPERATORS} \right]^2} \right]$$



USAR Test Arena Proliferation

FOSTERING COLLABORATION THROUGH STANDARDS

PREVIOUS COMPETITIONS

AAAI Conference 2000
AUSTIN, TEXAS, USA

IJCAI/AAAI Conference 2001
SEATTLE, WASHINGTON, USA

RoboCupRescue 2002
FUKUOKA, JAPAN

AAAI Conference 2002
EDMONTON, ALBERTA, CANADA

American Open 2003
PENNSYLVANIA, USA

Japan Open 2003
NIIGATA, JAPAN

RoboCupRescue 2003
PADUA, ITALY

IJCAI/AAAI Conference 2003
ACAPULCO, MEXICO

YEAR-ROUND ARENAS

NIST
MARYLAND, USA (2000)

Museum of Emerging Science
TOKYO, JAPAN (2002)

Carnegie Mellon University
PENNSYLVANIA, USA (2003)

Instituto Superiore Anticendi
ROME, ITALY (2003)

2004 COMPETITIONS

American Open

German Open

Japan Open

RoboCupRescue
LISBON, PORTUGAL

AAAI Conference
CALIFORNIA, USA

HIGH RESOLUTION LADAR FOR TERRAIN CHARACTERIZATION

**NIST HMMWV
at Tooele Army Depot
Dec. 9-13, 2002**

Mike Shneier, Tsai Hong, Tommy Chang,
Harry Scott, Steve Legowik, Gerry Cheok, Chuck Giauque
Intelligent Systems Division
National Institute of Standards and Technology





Terrain Characterization Testbed





Terrain Characterization



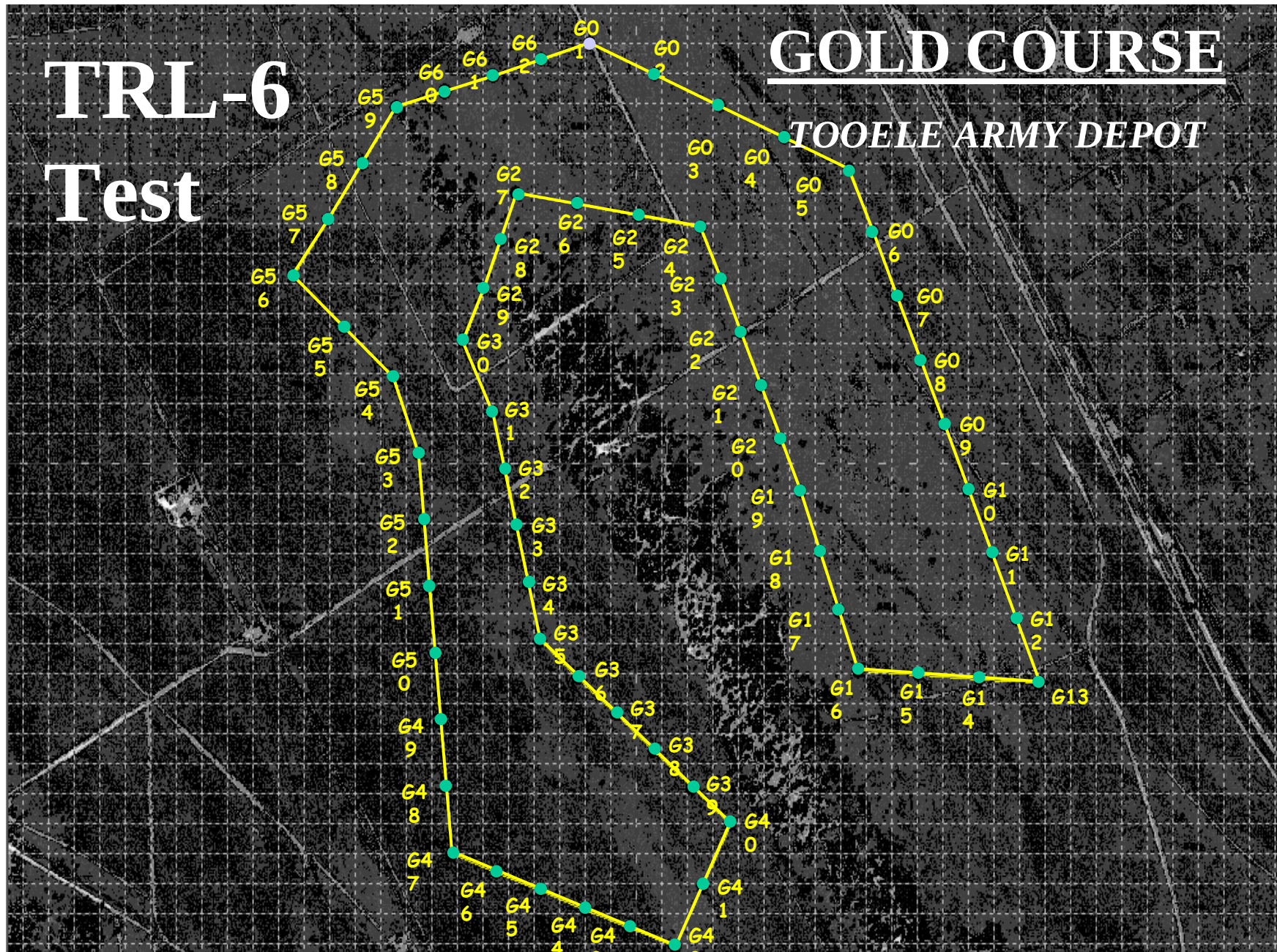
Testbed at Tooele Army Depot



TRL-6 Test

GOLD COURSE

TOOELE ARMY DEPOT

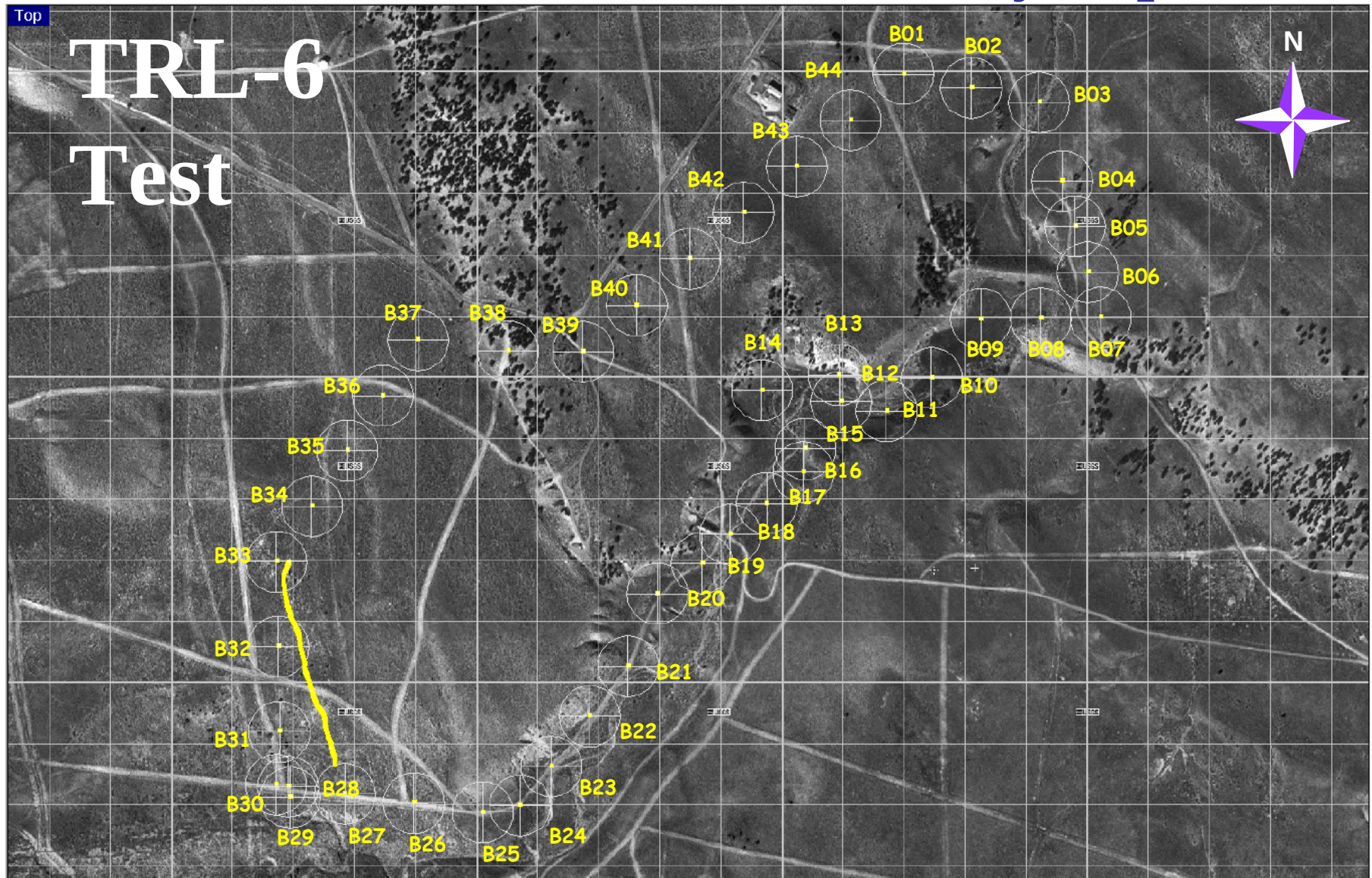


**GENERAL
DYNAMICS**
Robotic Systems



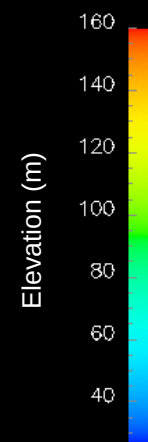
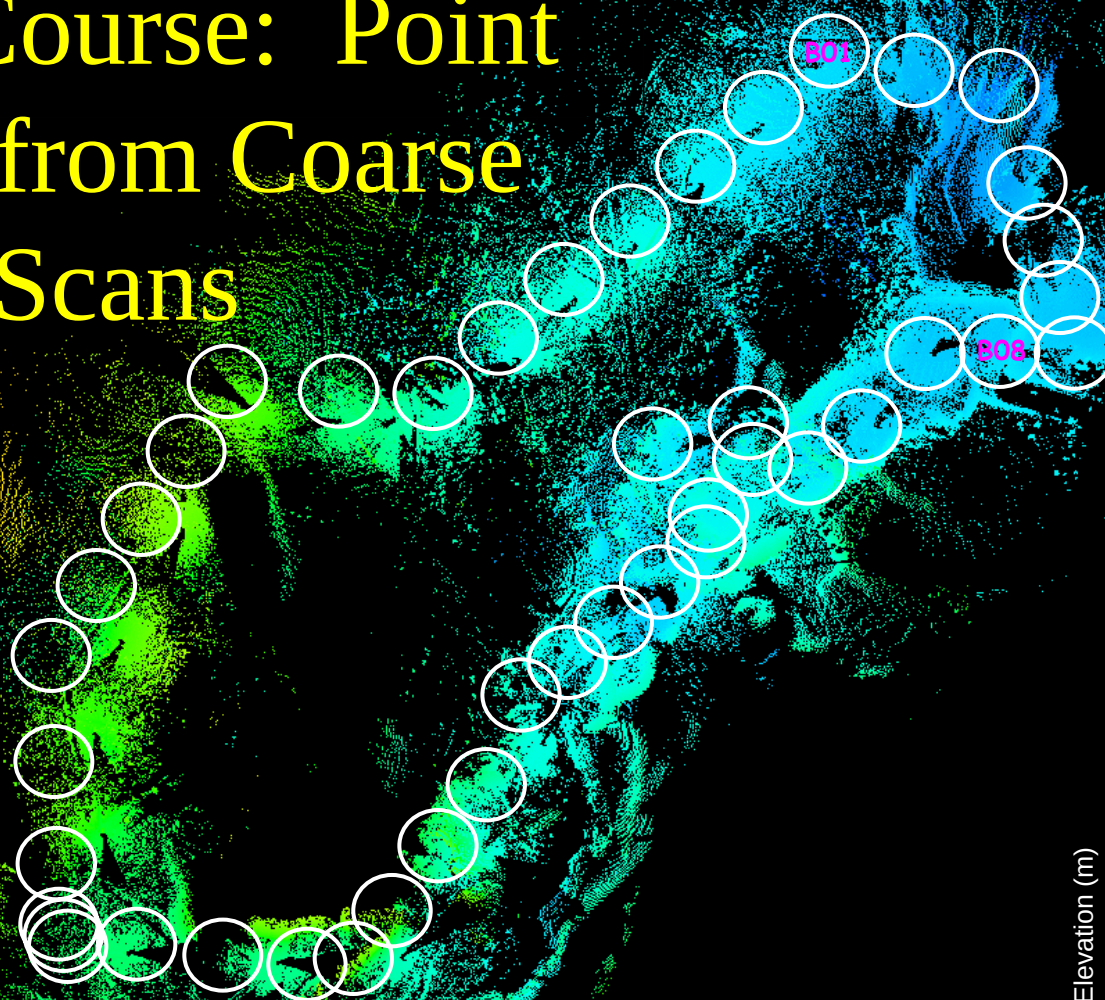
NIST • Manufacturing Engineering Laboratory • Intelligent Systems Division

Black Course: Tooele Army Depot





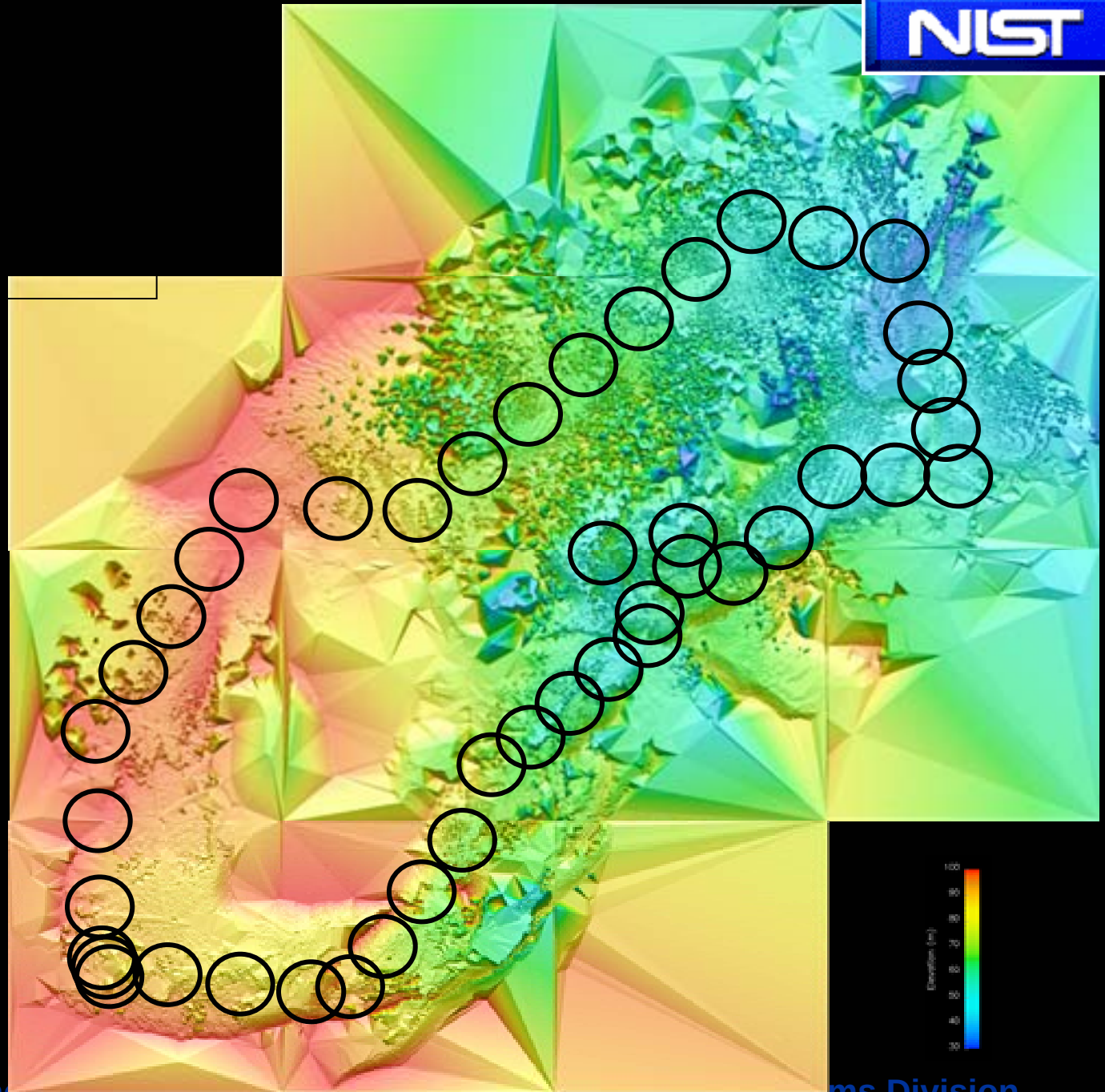
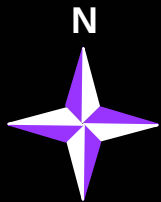
Black Course: Point Cloud from Coarse Scans





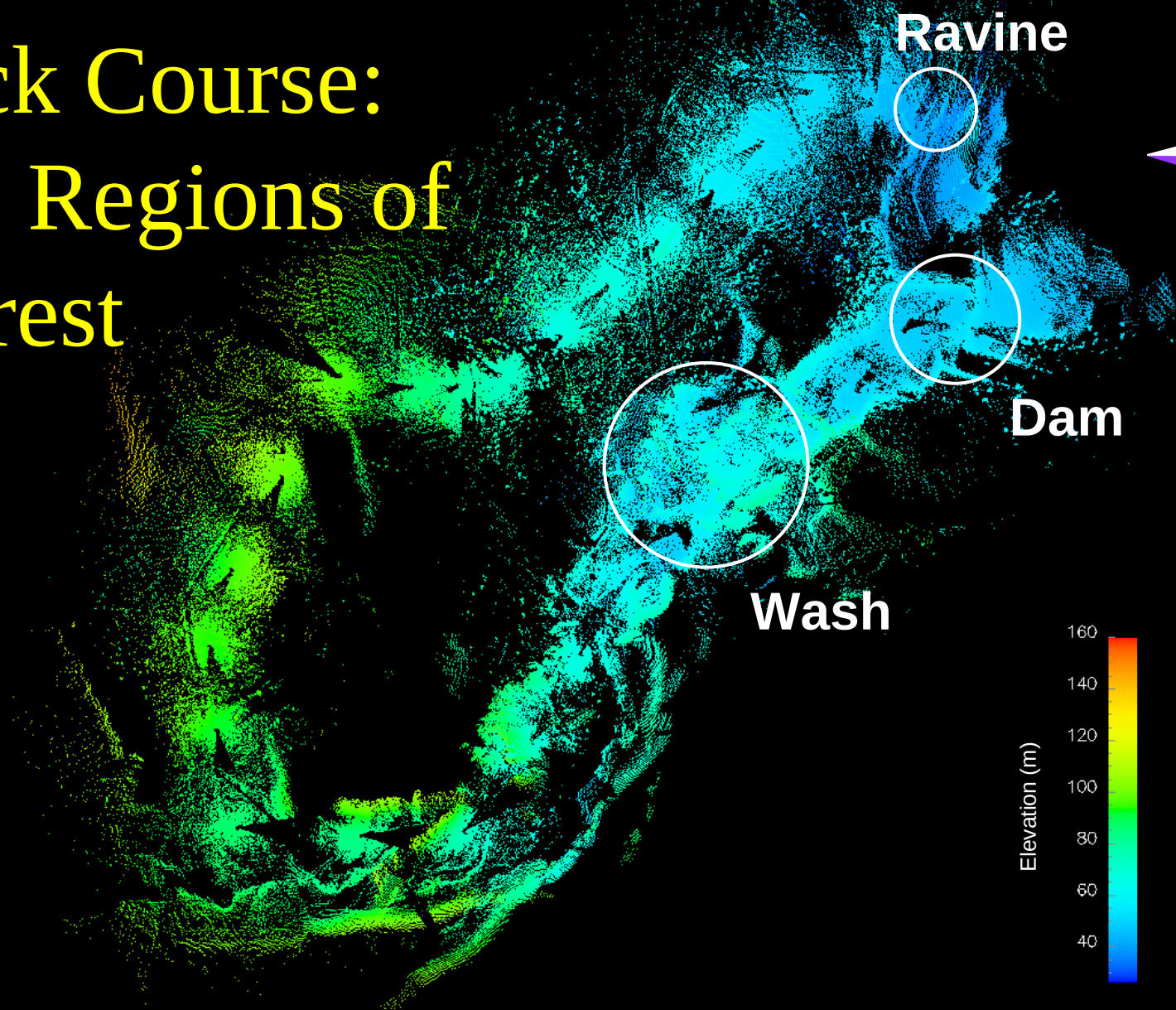
Black Course: Surface

1800 m





Black Course: Regions of Interest

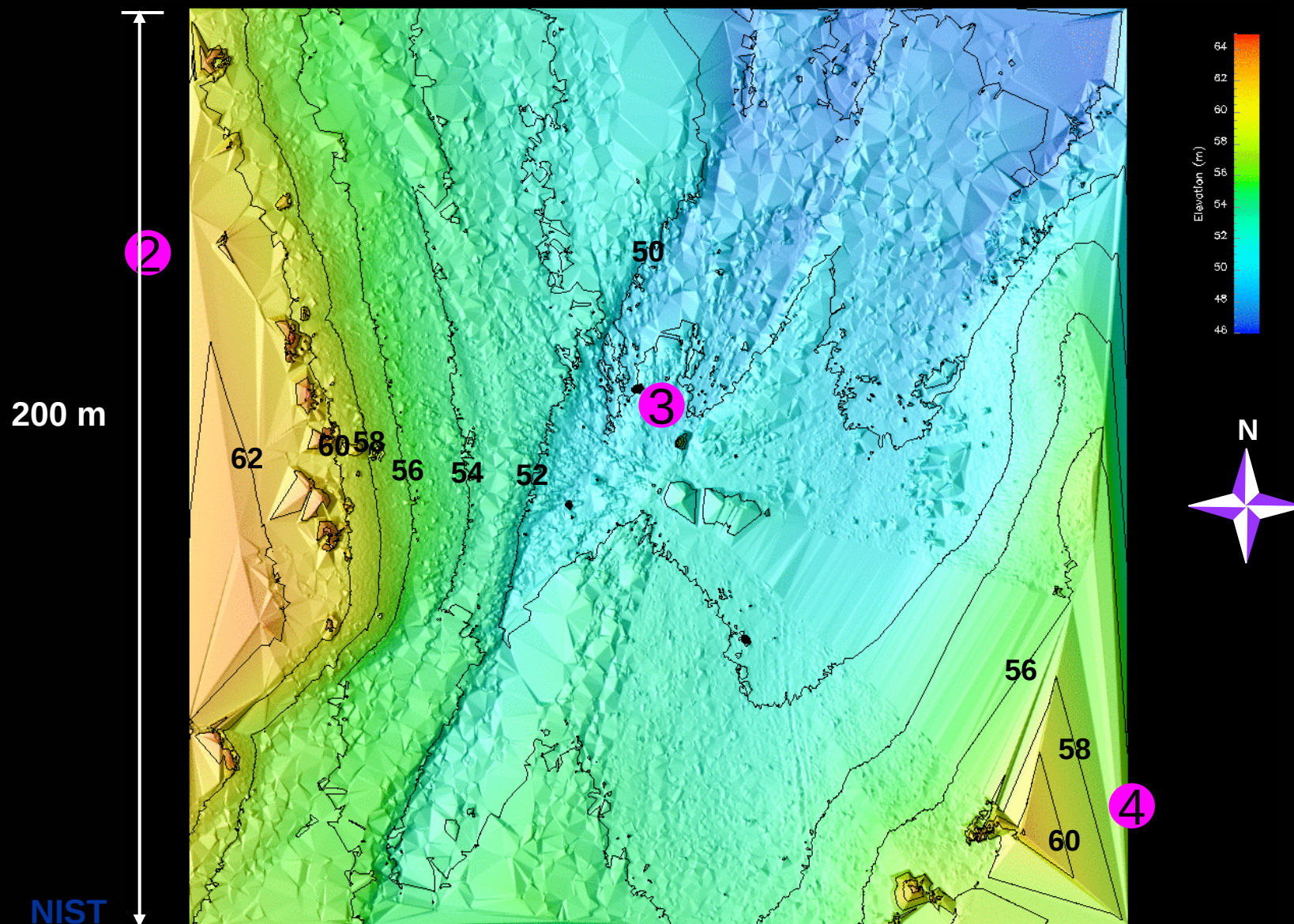




Ravine

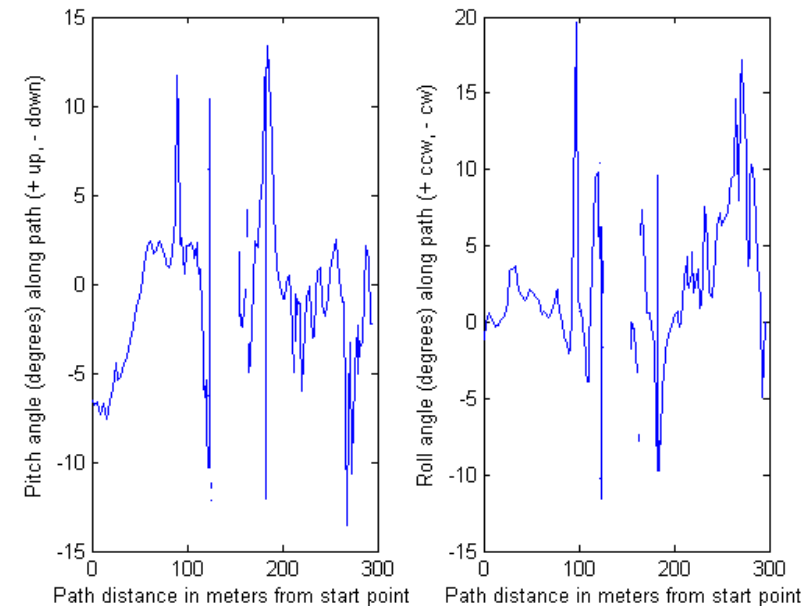
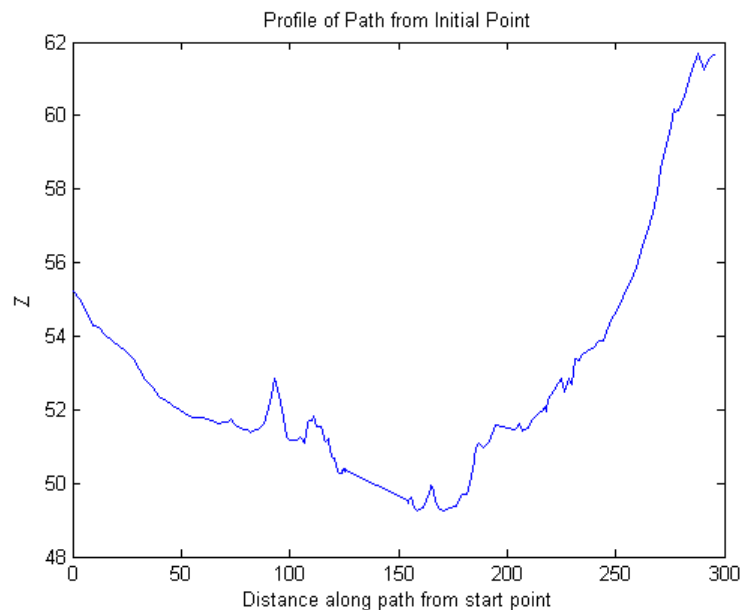
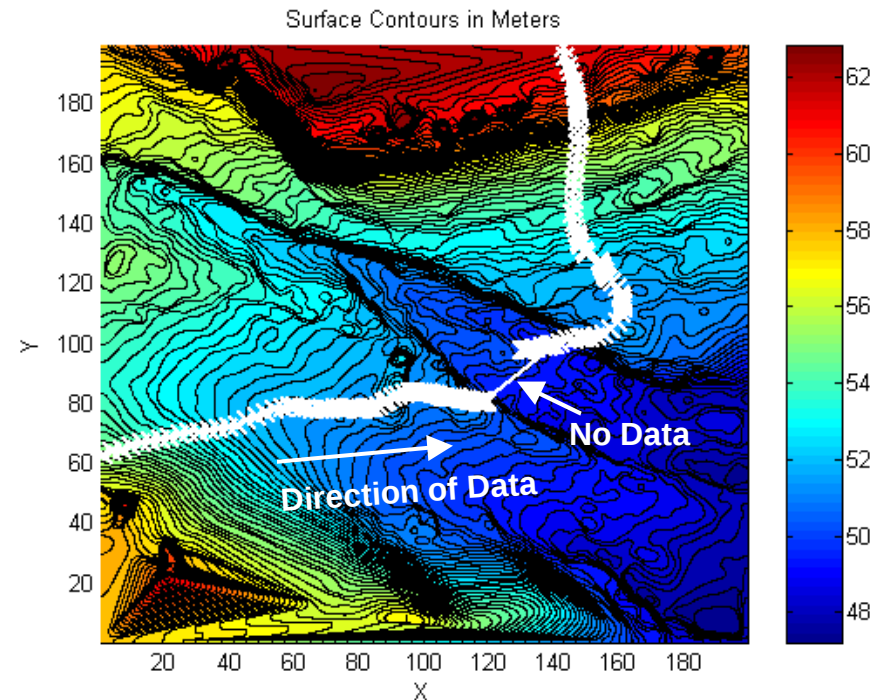


200x200 m, 16cm grid size, Overhead View



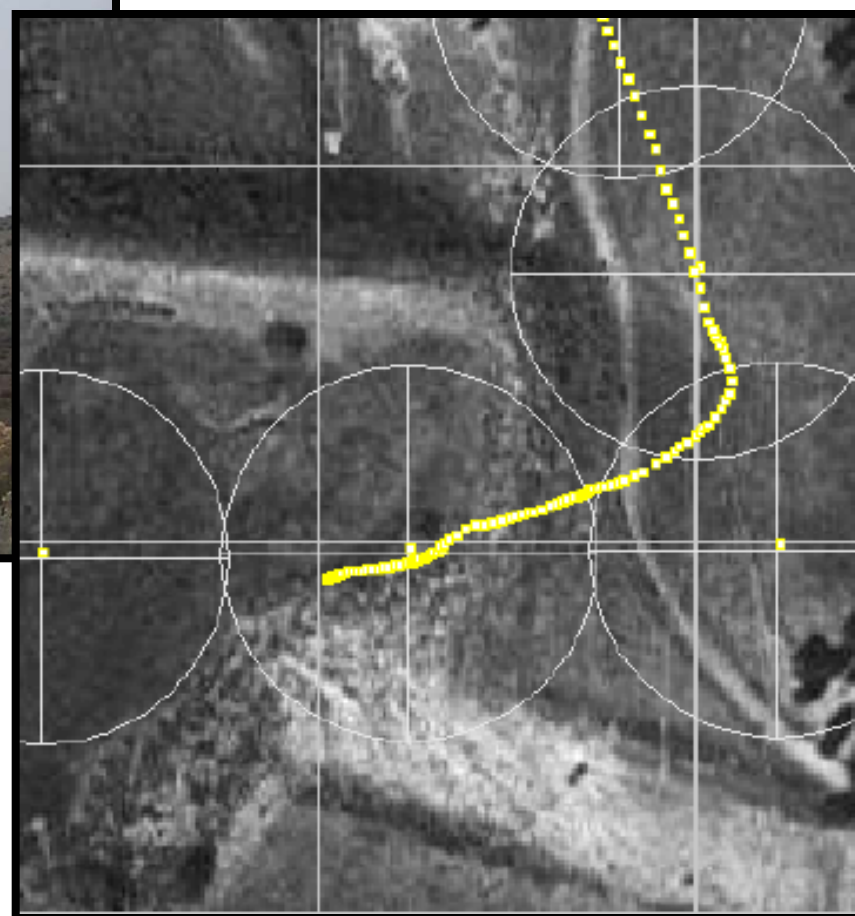
Estimated Pitch and Roll for Ravine1 200 x 200 m

- Surface contour intervals set @ 0.2 m.
- Path data begins at approximately (0, 60) and proceeds to the right.
- Note gap in the path data leads to a gap in the roll and pitch plots.





E-STOP 94 on the Dam

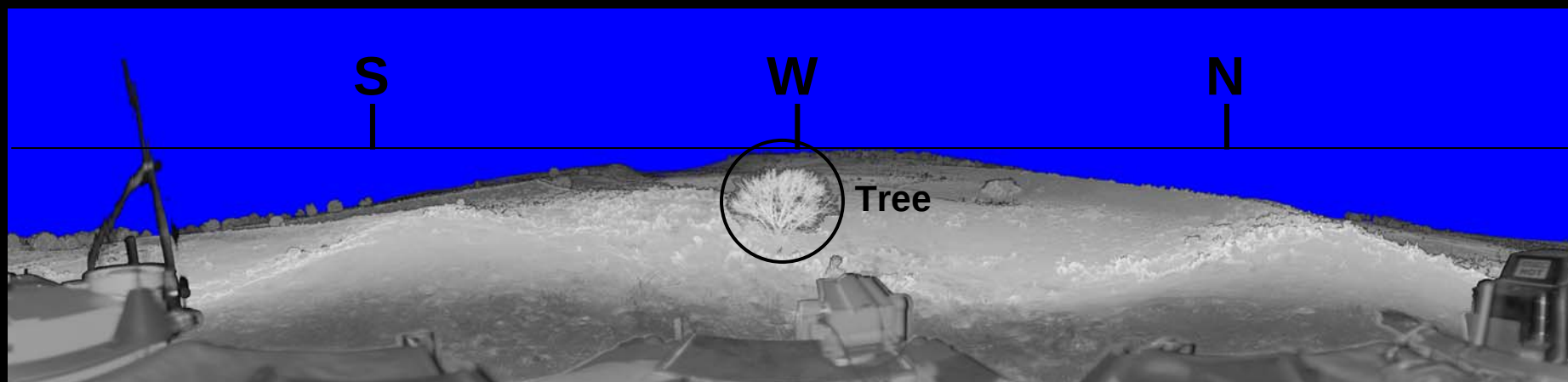




E-Stop 94 on the Dam



View Point 2 LADAR intensity image



CCD Camera Image composite

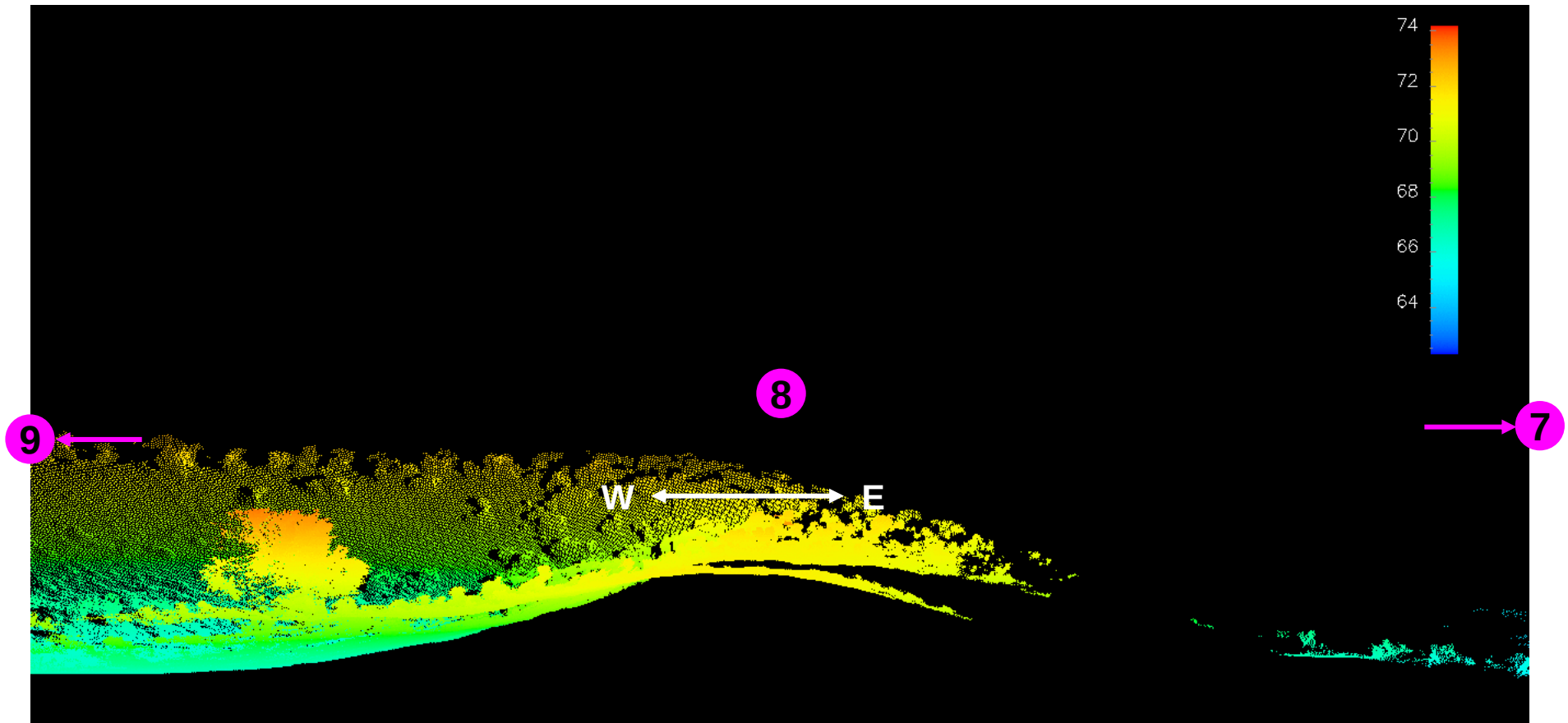




E-Stop 94

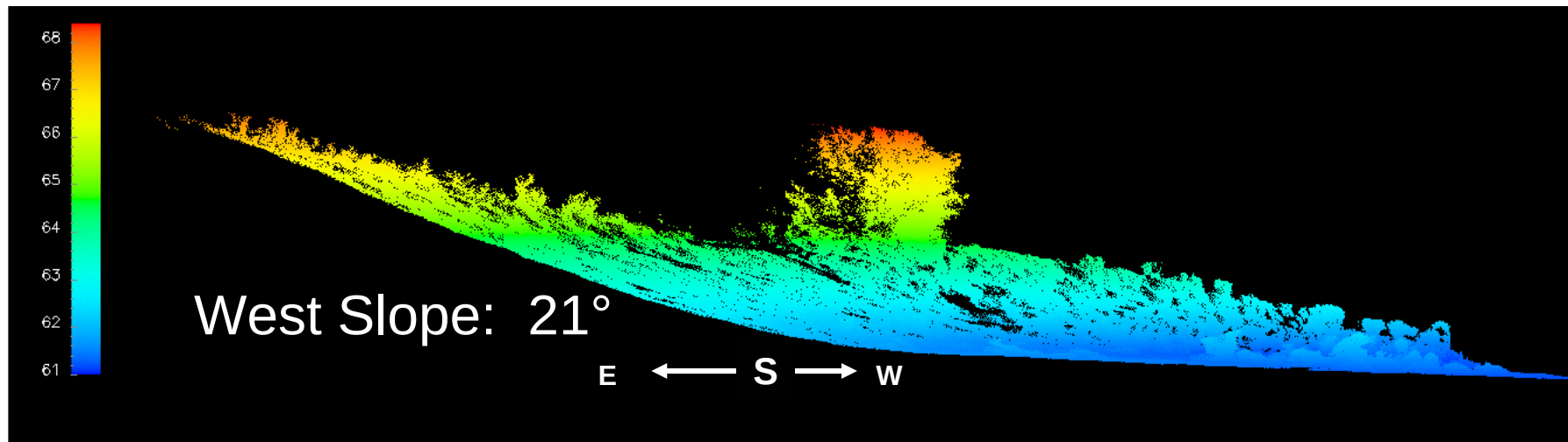
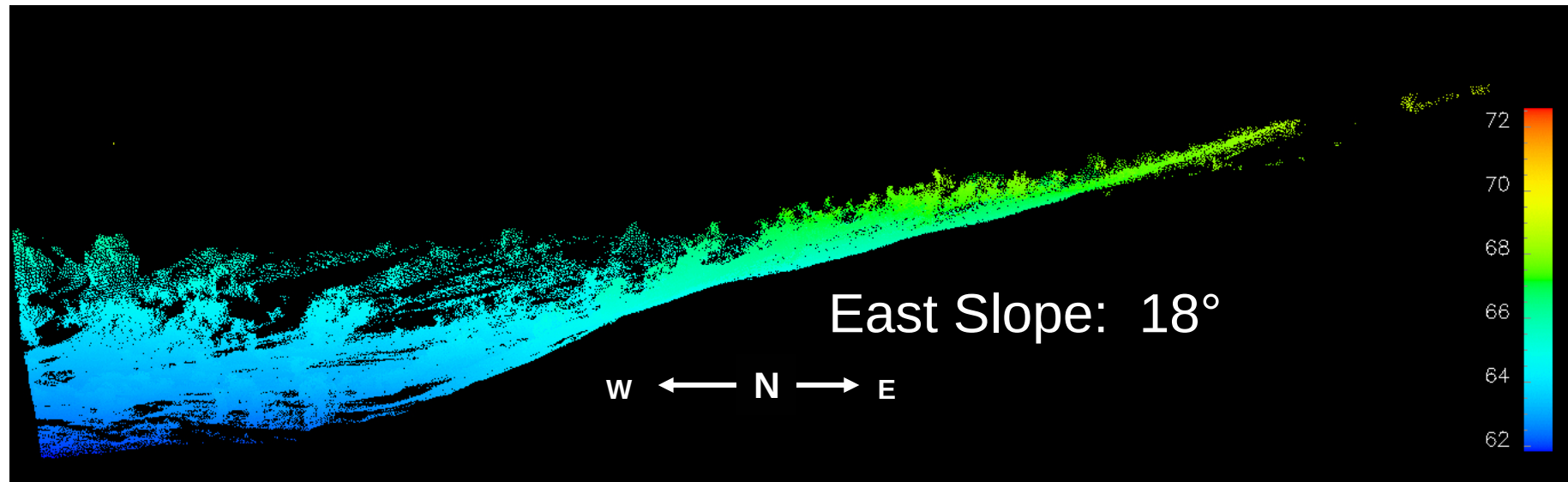
View Point 2 Looking Northward

X-section showing slopes of dam





Ground Slope on the Dam

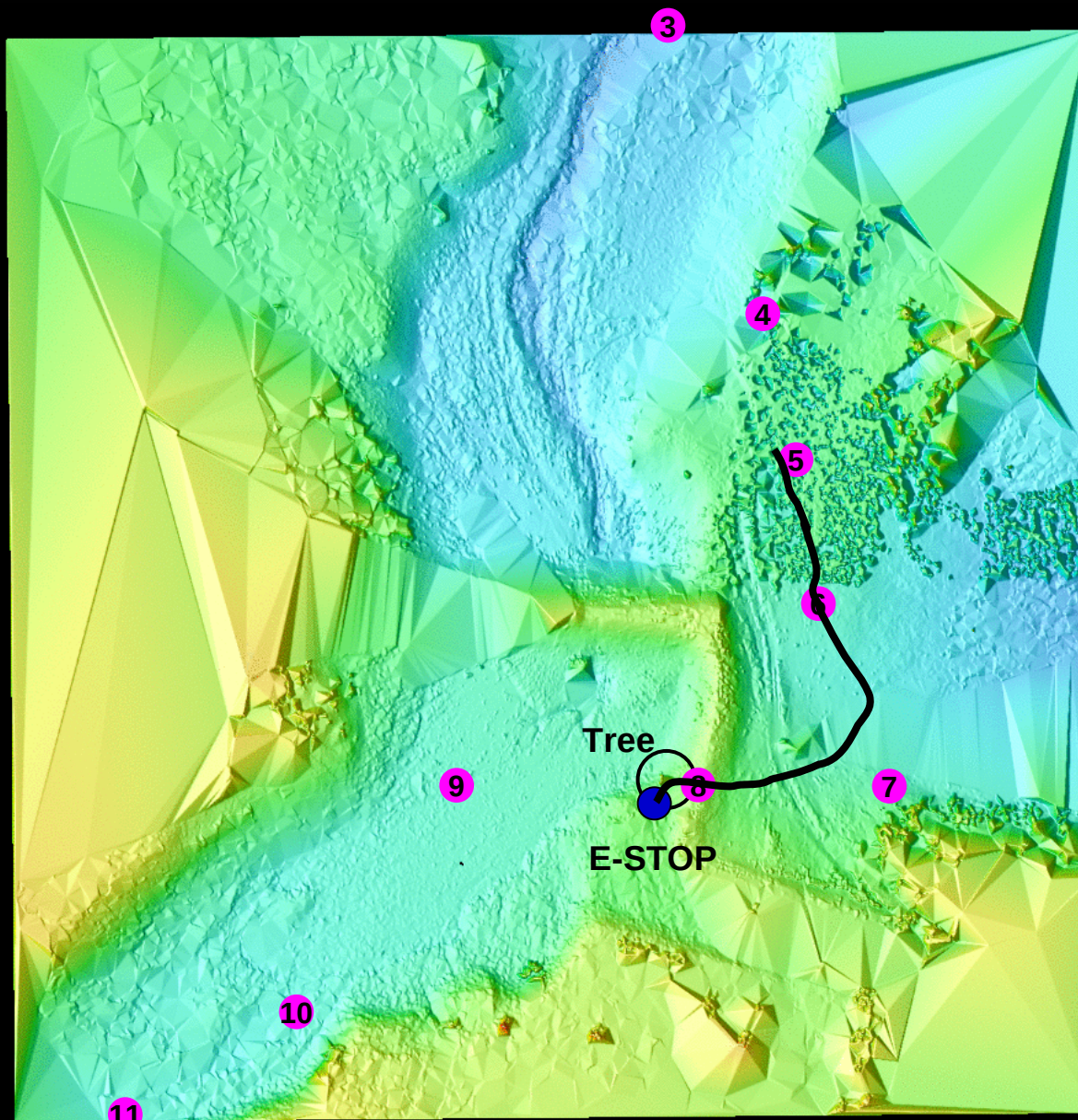




E-STOP 94 on the Dam



500 m



Elevation (m)

80

75

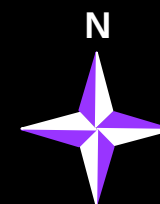
70

65

60

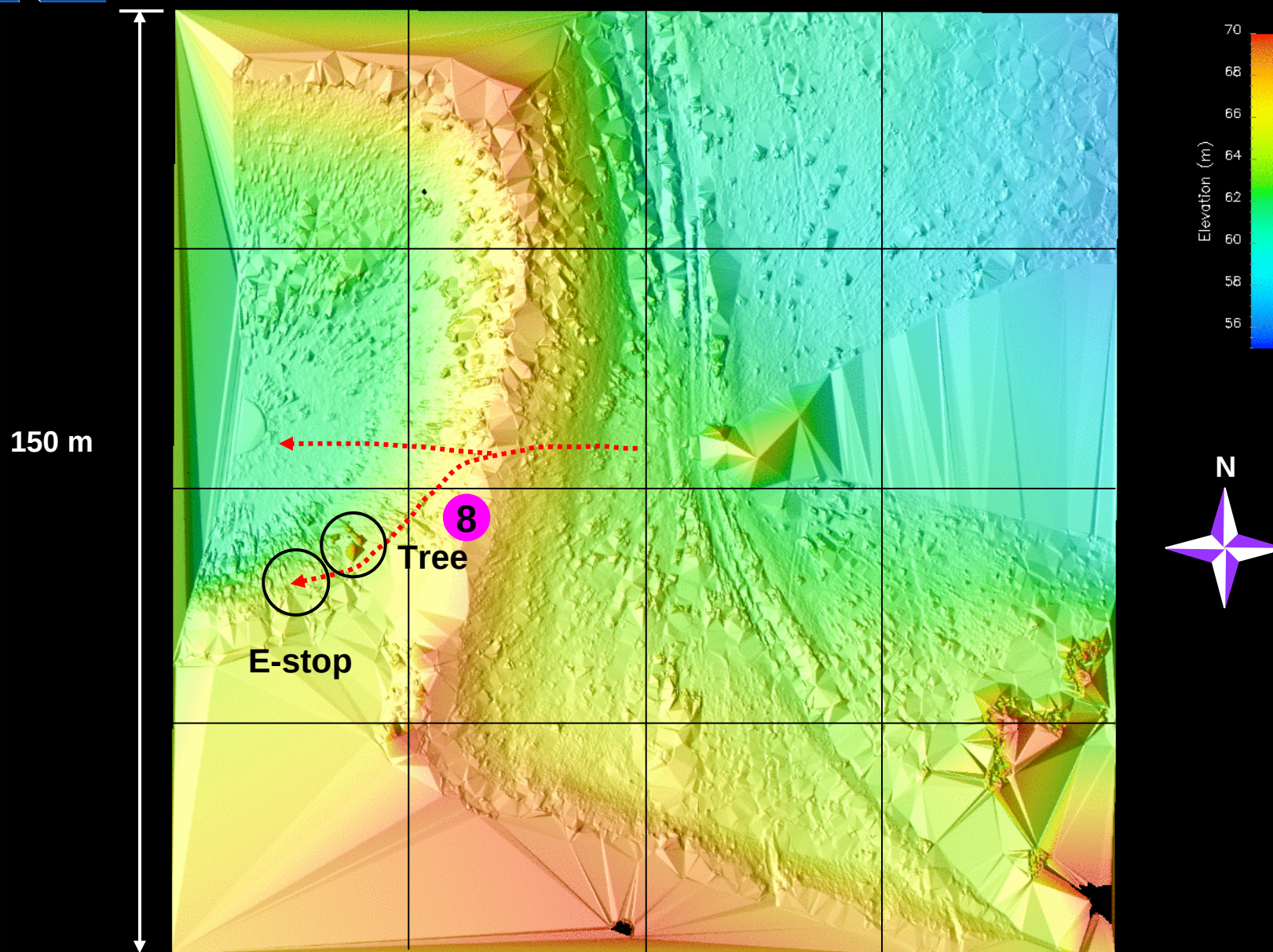
55

50



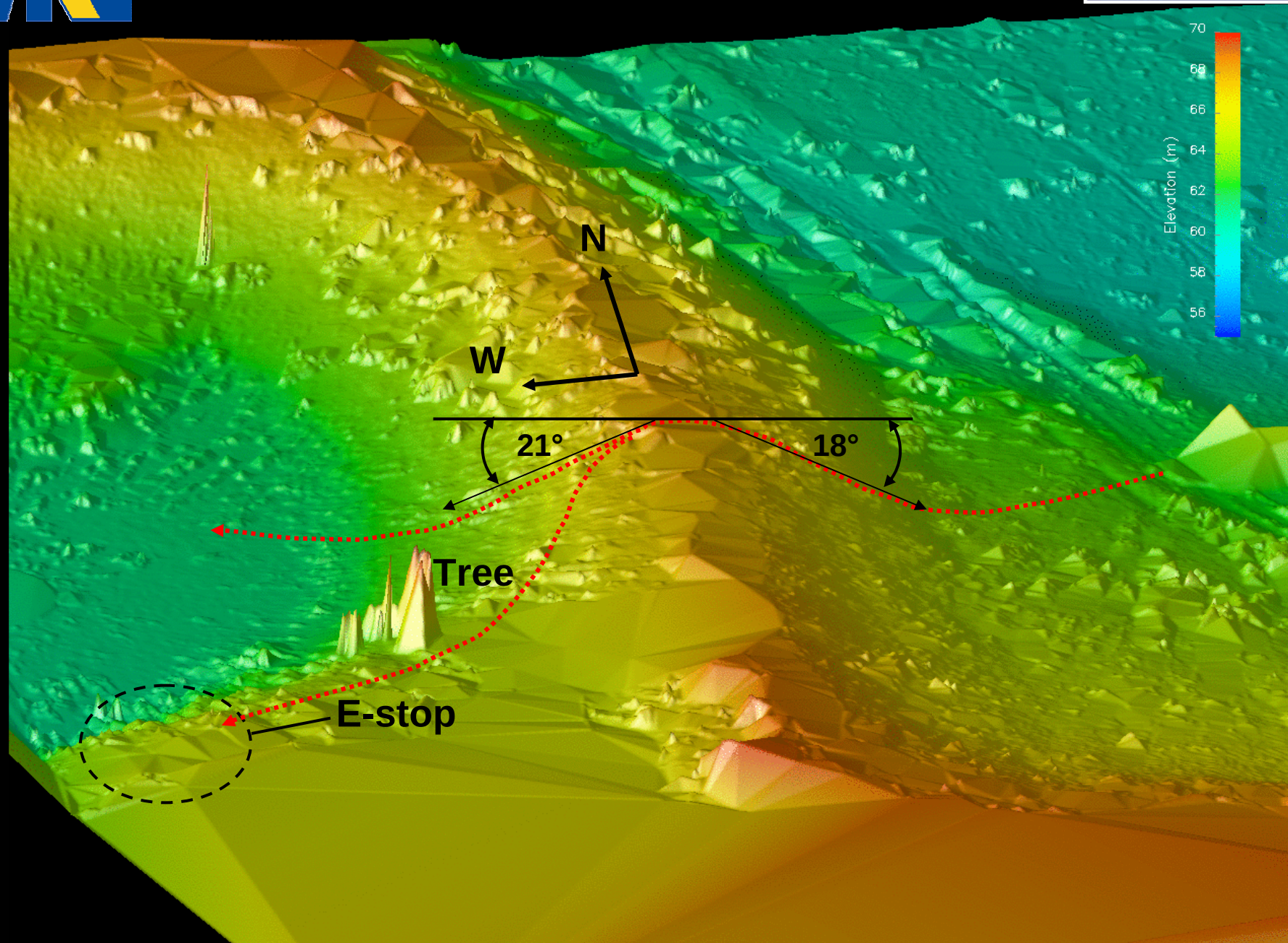


E-STOP 94 on the Dam





E-STOP 94 on the Dam



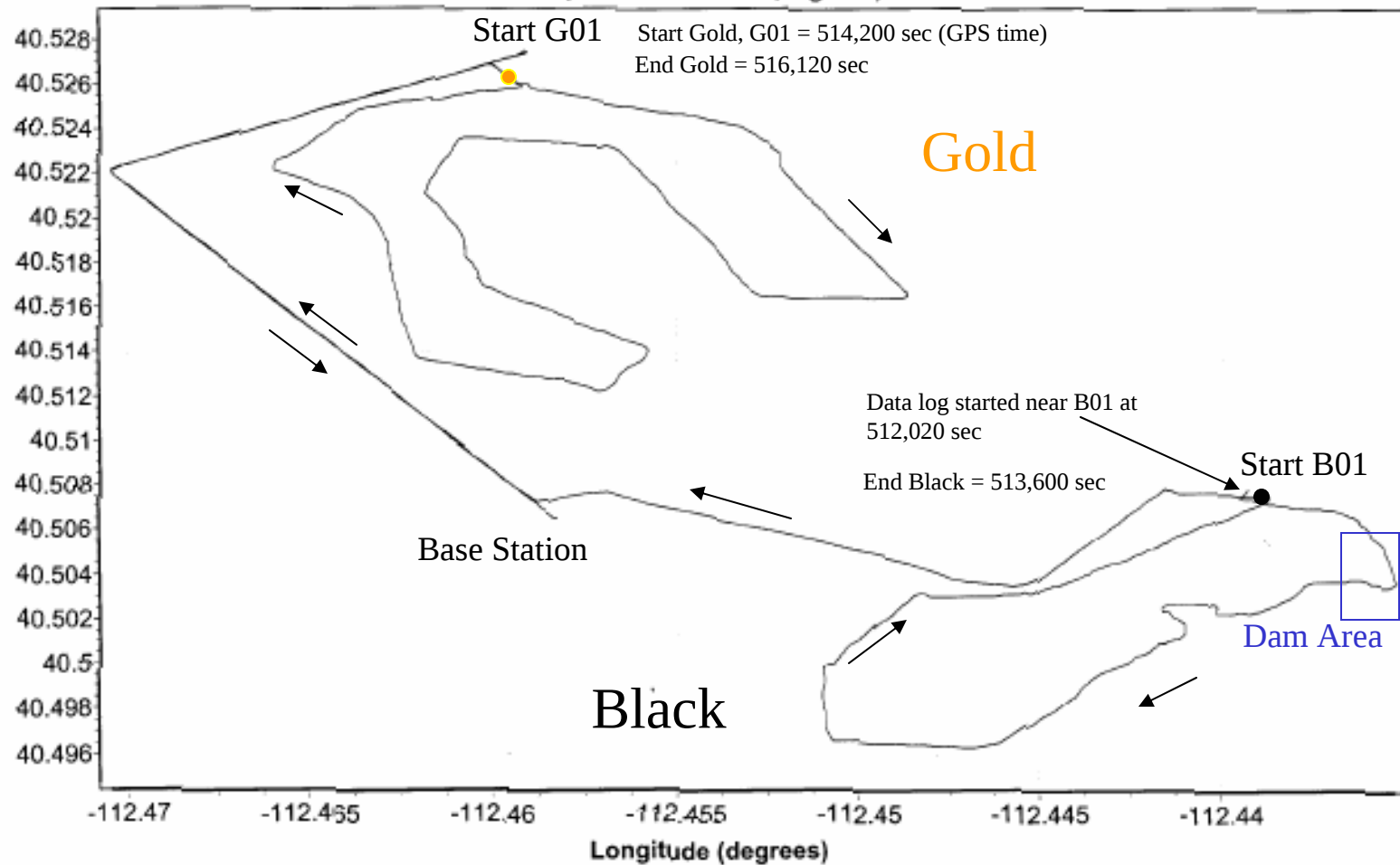
Terrain Analysis Using High Performance INS/GPs

**ARL/NIST HMMWV
at Tooele Army Depot
Dec. 9-13, 2002**

Harry Scott, Steve Legowik, Mike Shneier, Tsai Hong, Tommy Chang,
Harry Scott, Steve Legowik, Gerry Cheok, Chuck Giauque
Intelligent Systems Division
National Institute of Standards and Technology



CW around Black then CW around Gold



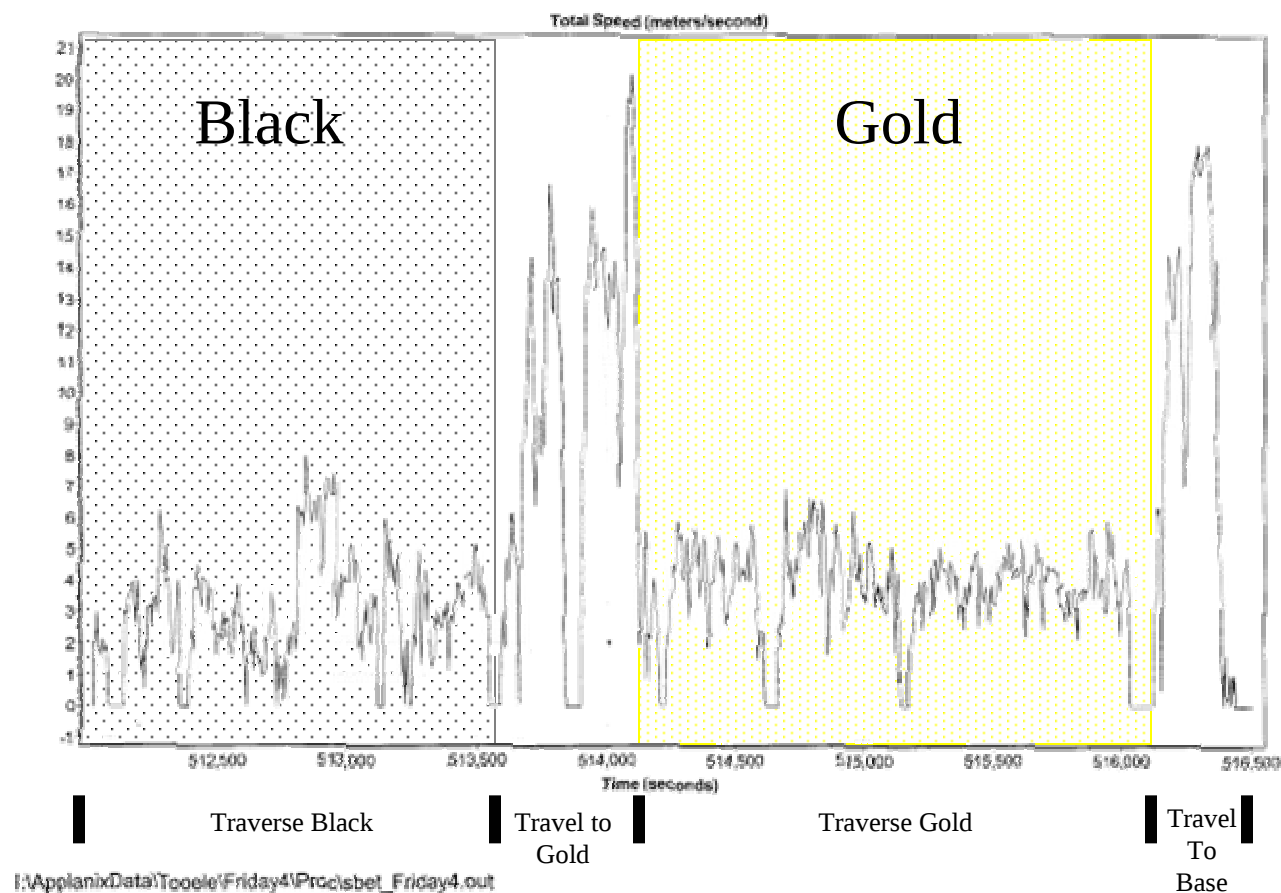


Speed

POSPac Version 4

SBET Navigation Data
- 1 -

1/7/2003 - 10:00:37 AM





Pitch

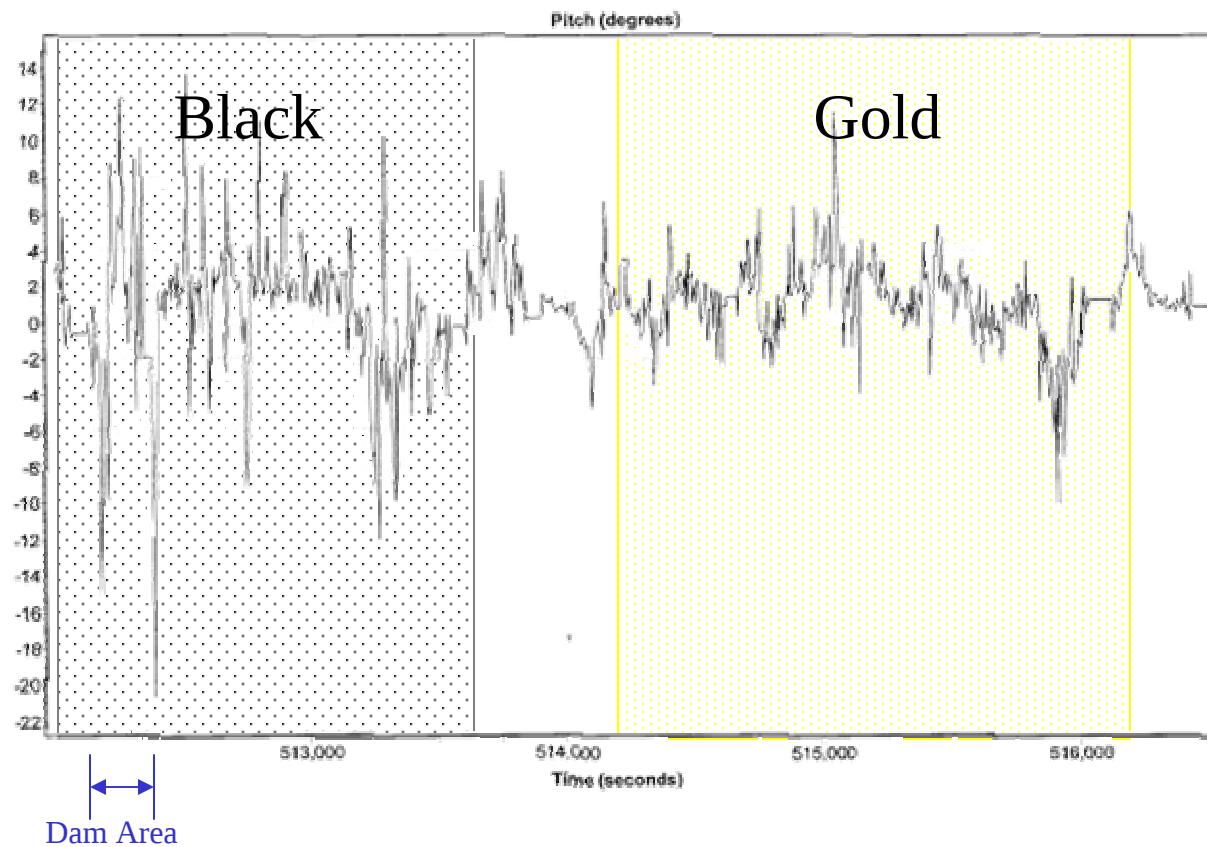


POSPac Version 4

SBET Navigation Data

- 1 -

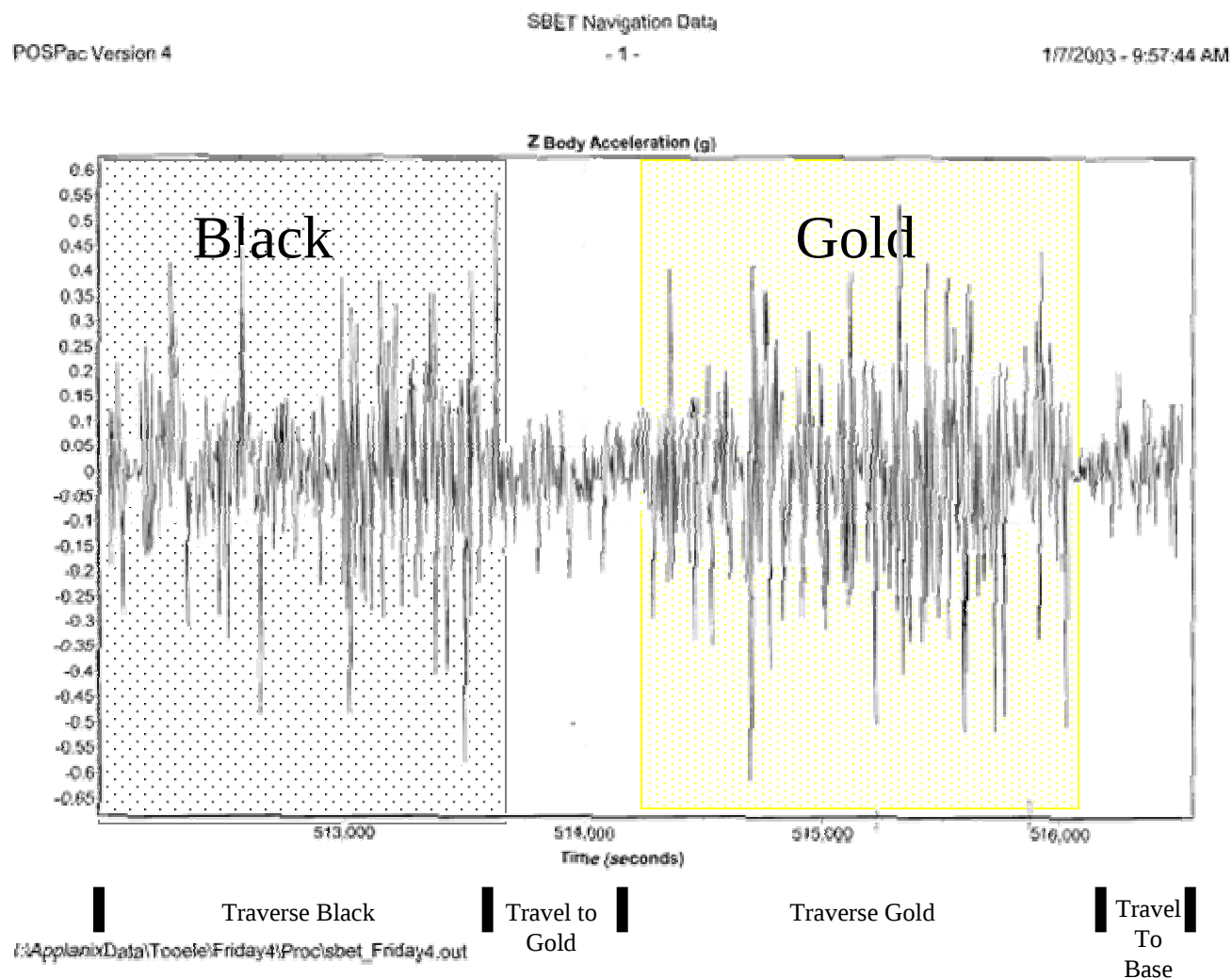
1/7/2003 - 9:58:08 AM



I:\App\anixData\Tooele\Friday4\Proc\sbet_Friday4.out

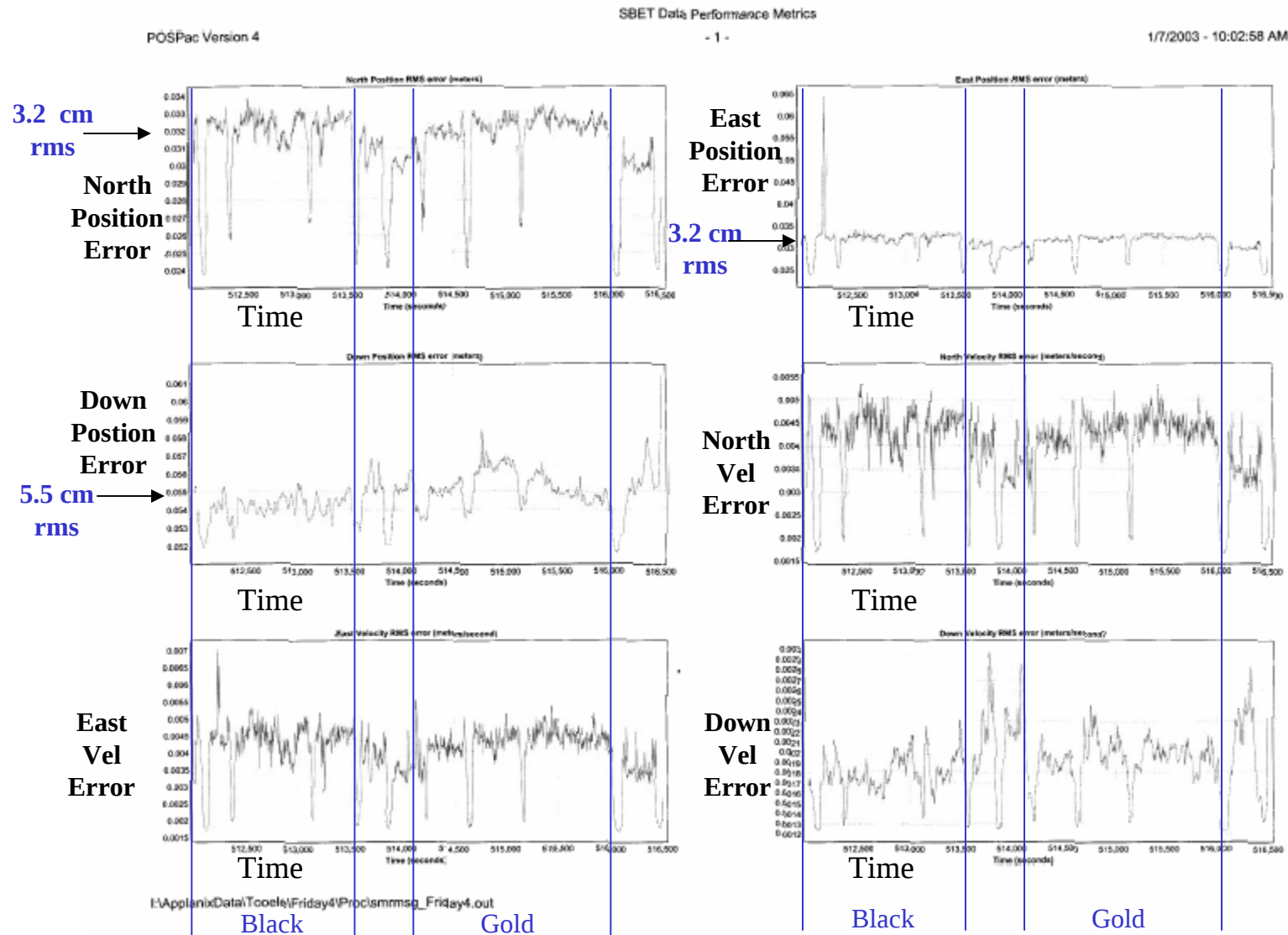


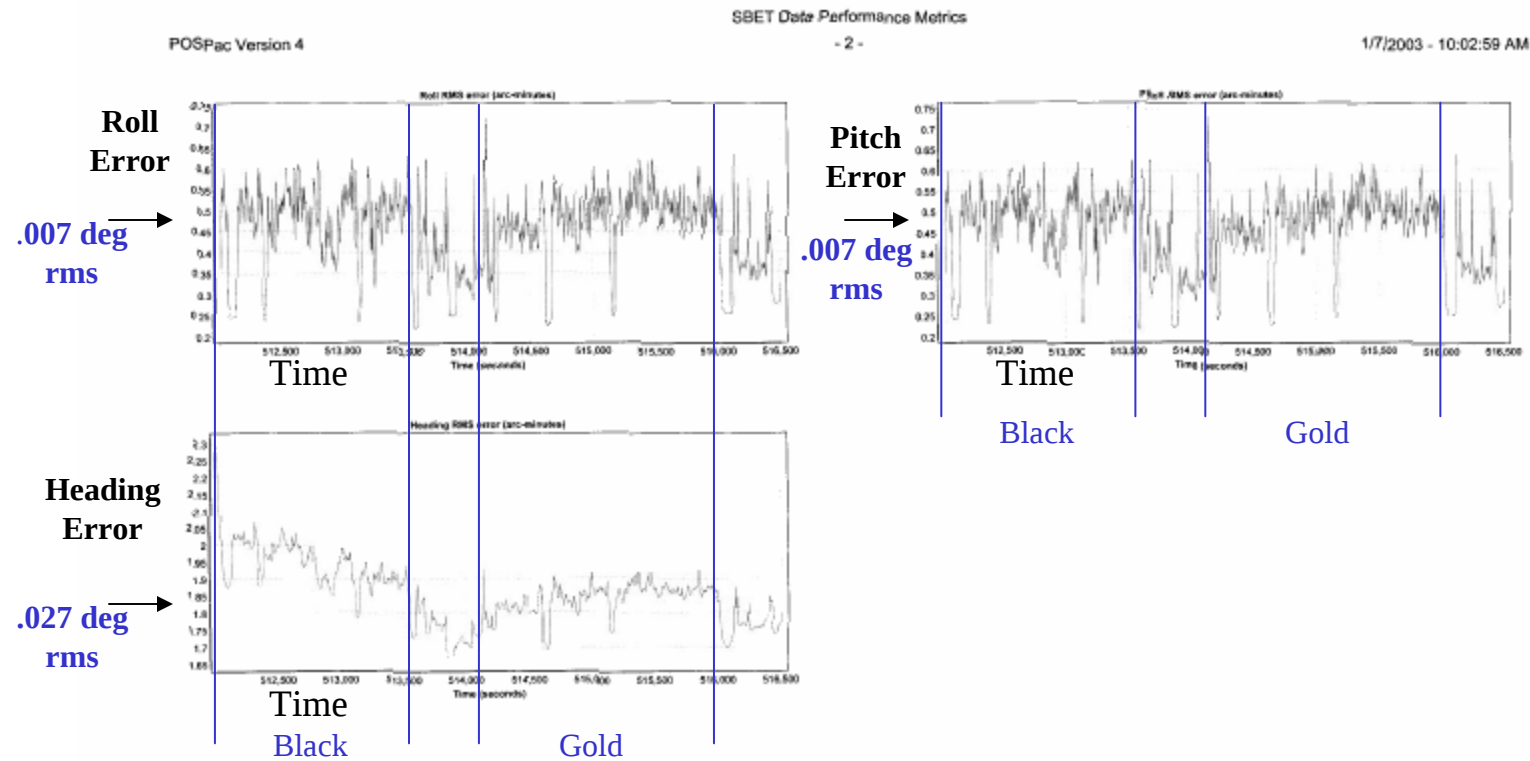
Z (vertical) Acceleration





Nav Performance Data



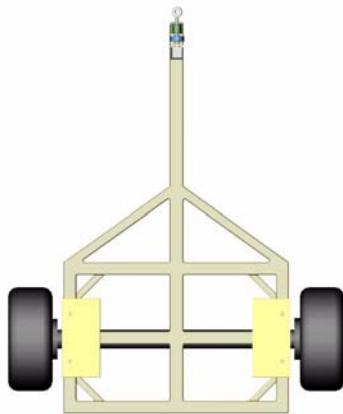


I:\ApplanixData\Tocele\Friday4\Proc\smmsg_Friday4.out



TARDEC Instrumented Trailer for Measurement of Soil Mechanics

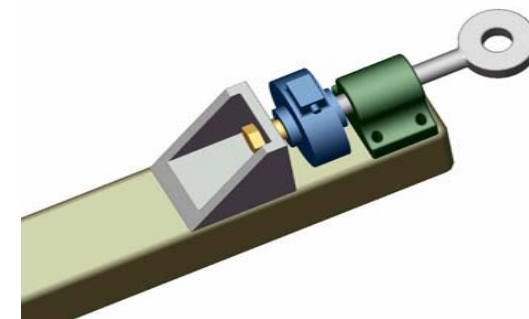
- Features of TARDEC Trailer:
 - Load cell/strain gage on trailer tongue with signal conditioning
 - Electronic braking/micro-processor controlled (for rolling resistance and ground friction measurements)
 - Variable load on trailer axle (bolted steel plates – matches XUV loading)
 - XUV tires and 12” ground clearance on trailer (highly mobile)



Top View



Isometric View

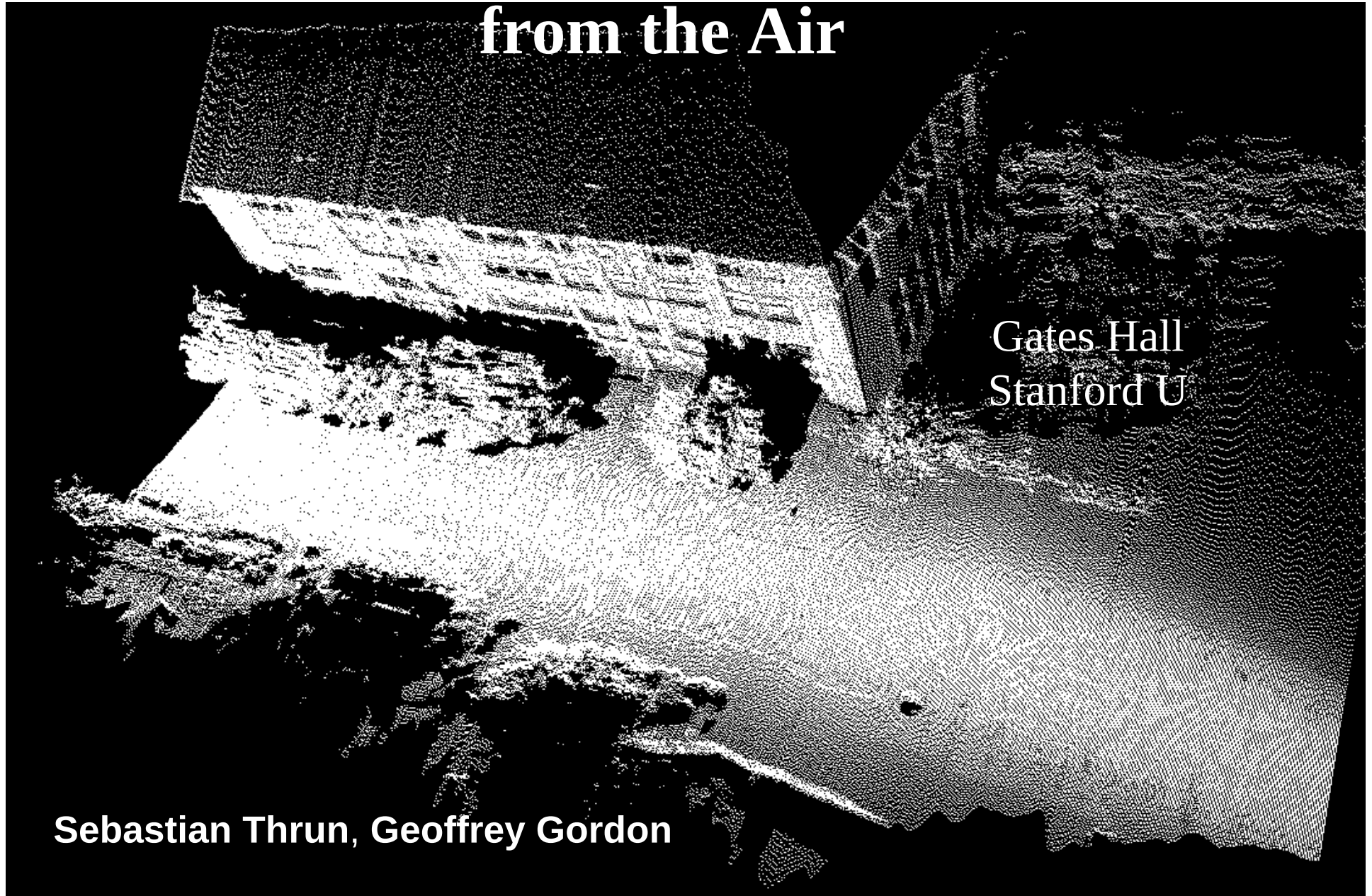


Trailer Hitch

TARDEC Instrumented Trailer at Tooele Army Depot



Terrain Characterization from the Air



Gates Hall
Stanford U

Sebastian Thrun, Geoffrey Gordon

Active Volumetric Mapping



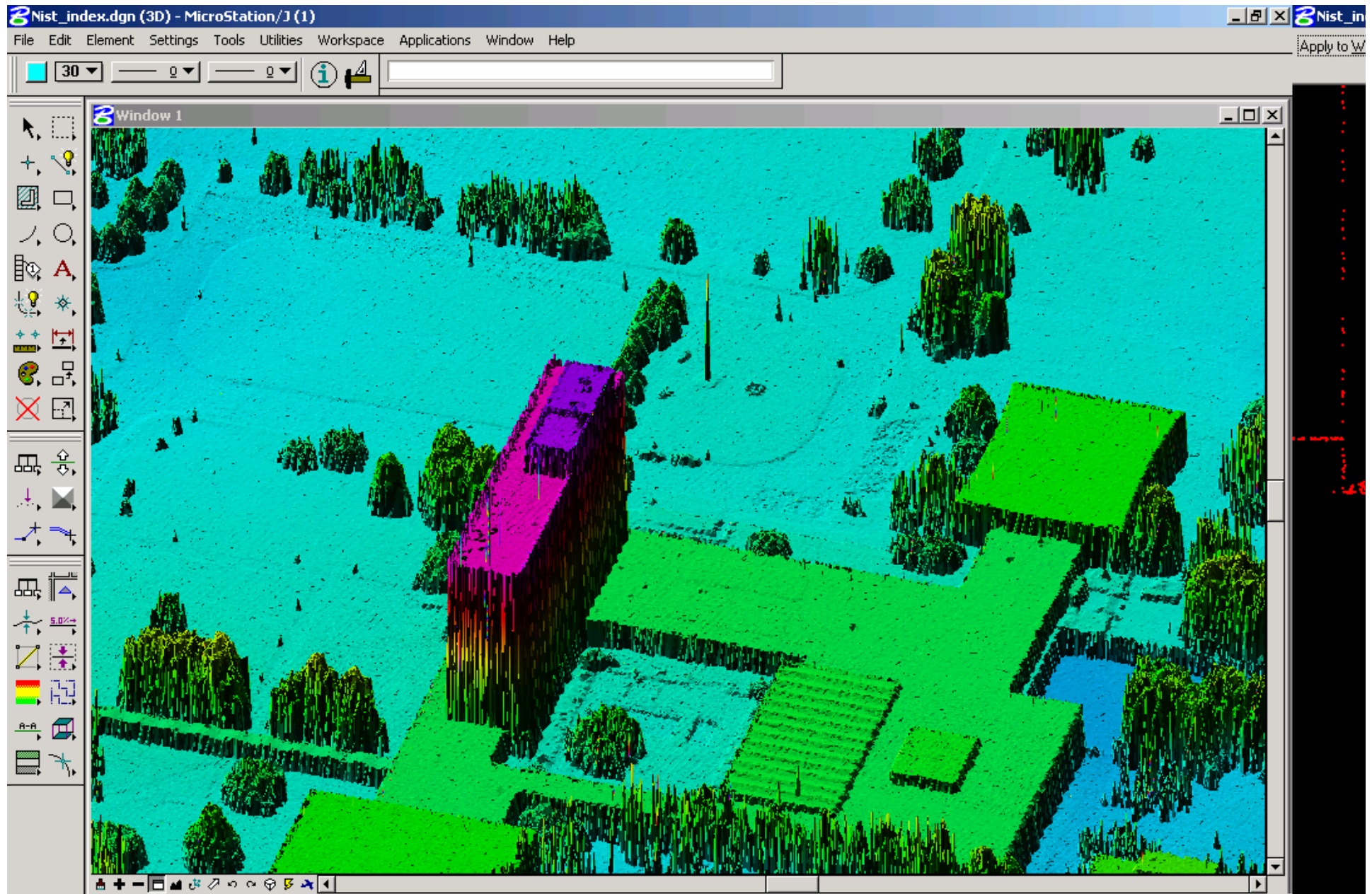
Sebastian Thrun, Geoffrey Gordon

Gates Hall, Stanford U

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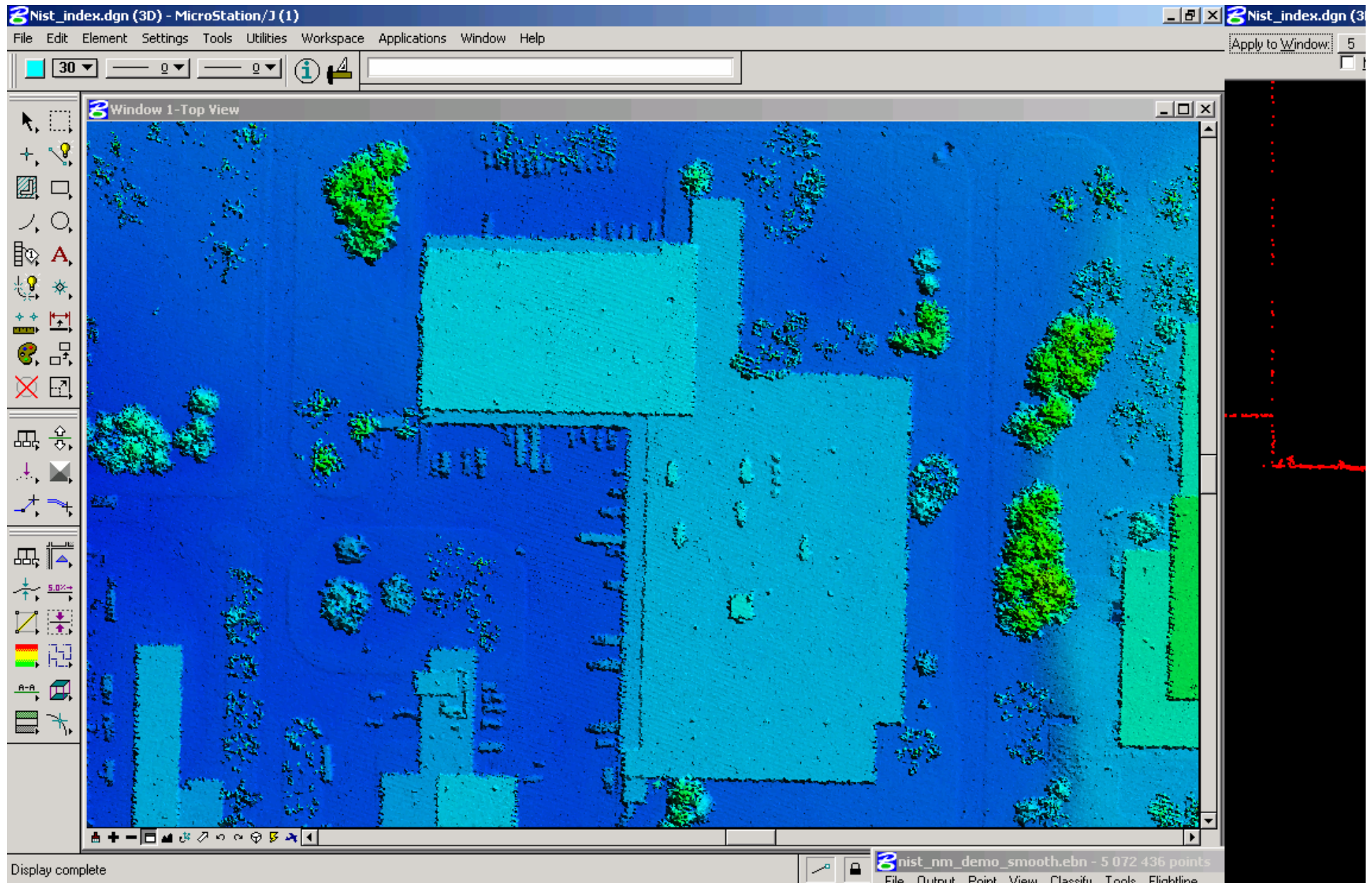


Ground Truth at NIST





Ground Truth at NIST





Technology Requirements for Autonomous On-Road Driving



Analysis of tasks

what? when? why? how? where?

**Decomposition into levels based on
range and resolution in time & space**

**Analysis of knowledge requirements
geometry, dynamics, entities, events, situations**

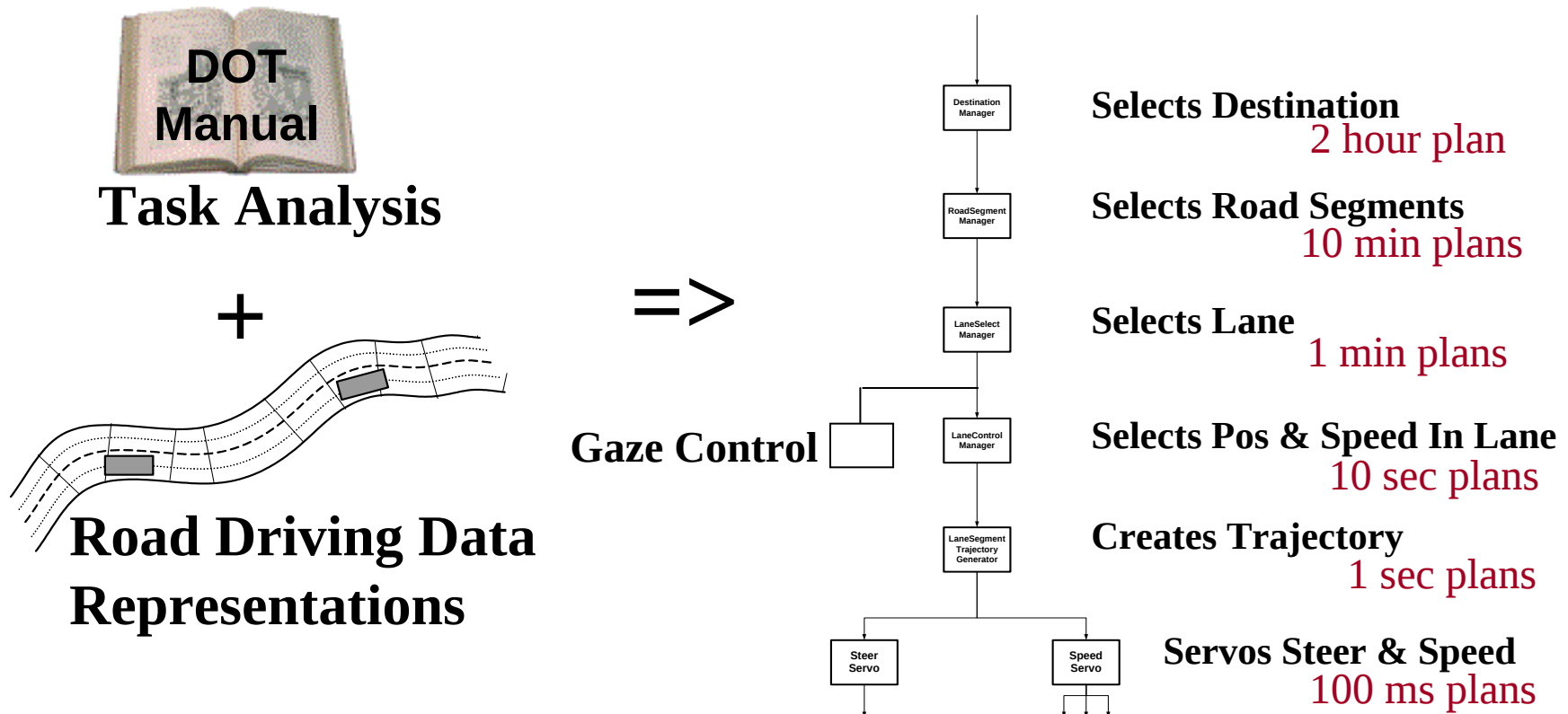
**Analysis of sensor requirements
field of view, resolution in time and space**



Driving Task Analysis



1) Analyze Autonomous Driving Tasks & Develop a Task Architecture

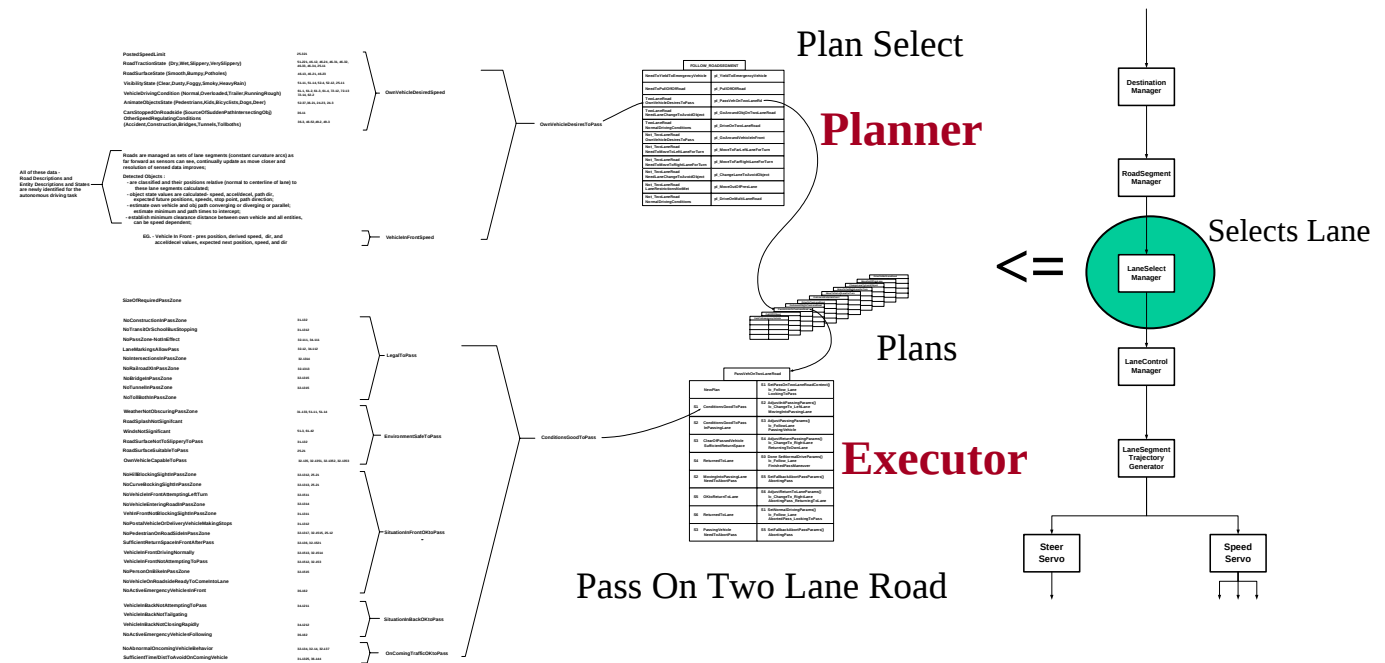




Driving Task Analysis



2) From task architecture, derive finite-state automata that encode task behaviors



World Model
Situation

Value
Judgment

Behavior
Generation



Driving Task Analysis



3) From FSMs, derive decision criteria and Value Judgments

World Model Situation

Value Judgment

Pass on Two Lane Road	
NewPlan	S1 SetPassOnTwoLaneRoadContext() lc_Follow_Lane LookingToPass
S1 ConditionsGoodToPass	S2 AdjustInitPassingParams() lc_ChangeTo_LeftLane MovingIntoPassingLane
S2 ConditionsGoodToPass InPassingLane	S3 AdjustPassingParams() lc_FollowLane PassingVehicle
S3 ClearOfPassedVehicle SufficientReturnSpace	S4 AdjustReturnPassingParams() lc_ChangeTo_RightLane ReturningToOwnLane
S4 ReturnedToLane	S0 DONE SetNormalDriveParams() lc_Follow_Lane FinishedPassManeuver
S2 MovingIntoPassingLane NeedToAbortPass	S5 SetFallbackAbortPassParams() AbortingPass
S5 OKtoReturnToLane	S6 AdjustReturnToLaneParams() lc_ChangeTo_RightLane AbortingPass_ReturningToLane
S6 ReturnedToLane	S1 SetNormalDrivingParams() lc_Follow_Lane AbortedPass_LookingToPass
S3 PassingVehicle NeedToAbortPass	S5 SetFallbackAbortPassParams() AbortingPass

Plan



Driving Task Analysis



4) Derive dependencies on World Model Situations

ConditionsGoodToPass

PassVehOnTwoLaneRoad	
NewPlan	S1 SetPassOnTwoLaneRoadContext() lc_Follow_Lane LookingToPass
S1 ConditionsGoodToPass	S2 AdjustInitPassingParams() lc_ChangeTo_LeftLane MovingIntoPassingLane
S2 ConditionsGoodToPass InPassingLane	S3 AdjustPassingParams() lc_FollowLane PassingVehicle
S3 ClearOfPassedVehicle SufficientReturnSpace	S4 AdjustReturnPassingParams() lc_ChangeTo_RightLane ReturningToOwnLane
S4 ReturnedToLane	S0 Done SetNormalDriveParams() lc_Follow_Lane FinishedPassManeuver
S2 MovingIntoPassingLane NeedToAbortPass	S5 SelfFallbackAbortPassParams() AbortingPass
S5 OKtoReturnToLane	S6 AdjustReturnToLaneParams() lc_ChangeTo_RightLane AbortingPass_ReturningToLane
S6 ReturnedToLane	S1 SetNormalDrivingParams() lc_Follow_Lane AbortedPass_LookingToPass
S3 PassingVehicle NeedToAbortPass	S5 SelfFallbackAbortPassParams() AbortingPass

Plan

Behavior

Generation

World Model Situation

Value Judgment

NoConstructionInPassZone
NoTransitOrSchoolBusStopping
NoPassZone-NotInEffect
LaneMarkingsAllowPass
NoIntersectionsInPassZone
NoRailroadXInPassZone
NoBridgeInPassZone
NoTunnelInPassZone
NoTollBoothInPassZone

LegalToPass

WeatherNotObscuringPassZone
RoadSplashNotSignificant
WindsNotSignificant
RoadSurfaceNotTooSlipperyToPass
RoadSurfaceSuitableToPass
OwnVehicleCapableToPass

EnvironmentSafeToPass

NoHillBlockingSightInPassZone
NoCurveBlockingSightInPassZone
NoVehicleFrontAttemptingLeftTurn
NoVehicleEnteringRoadInPassZone
VehInFrontNotBlockingSightInPassZone
NoPostalVehicleOrDeliveryVehicleMakingStops
NoPedestrianOnRoadSideInPassZone
SufficientReturnSpaceInFrontAfterPass
VehicleInFrontDrivingNormally
VehicleInFrontNotAttemptingToPass
NoPersonOnBikeInPassZone
NoVehicleOnRoadsideReadyToComeIntoLane
NoActiveEmergencyVehiclesInFront

SituationInFrontOKtoPass

NoConstructionInPassZone
NoTransitOrSchoolBusStopping
NoPassZone-NotInEffect
LaneMarkingsAllowPass

SituationInBackOKtoPass

NoIntersectionsInPassZone
NoRailroadXInPassZone

OnComingTrafficOKtoPass



Driving Task Analysis



NoConstructionInPassZone
NoTransitOrSchoolBusStopping
NoPassZone-NotInEffect
LaneMarkingsAllowPass
NoIntersectionsInPassZone
NoRailroadXInPassZone
NoBridgeInPassZone
NoTunnelInPassZone
NoTollBothInPassZone

World Model
Situation

**Estimated
~2000 situations**

5) Derive World Model Knowledge requirements

LegalToPass

EnvironmentSafeToPass

SituationInFrontOKtoPass

SituationInBackOKtoPass

OnComingTrafficOKtoPass

ConditionsGoodToPass

Value Judgment

Behavior
Generation

PassConditions	
1. ConditionsGoodToPass	11. InfractionOfTrafficLawNotCommitted
2. ConditionsGoodToPass	12. Follow_Lane
3. ConditionsGoodToPass	13. ChangeTo_LeftLane
4. ConditionsGoodToPass	14. ChangeTo_RightLane
5. ConditionsGoodToPass	15. Follow_Lane
6. ConditionsGoodToPass	16. Follow_Lane
7. ConditionsGoodToPass	17. Follow_Lane
8. ConditionsGoodToPass	18. Follow_Lane
9. ConditionsGoodToPass	19. Follow_Lane
10. ConditionsGoodToPass	20. Follow_Lane
11. ConditionsGoodToPass	21. Follow_Lane
12. ConditionsGoodToPass	22. Follow_Lane
13. ConditionsGoodToPass	23. Follow_Lane
14. ConditionsGoodToPass	24. Follow_Lane
15. ConditionsGoodToPass	25. Follow_Lane
16. ConditionsGoodToPass	26. Follow_Lane
17. ConditionsGoodToPass	27. Follow_Lane
18. ConditionsGoodToPass	28. Follow_Lane
19. ConditionsGoodToPass	29. Follow_Lane
20. ConditionsGoodToPass	30. Follow_Lane

**Estimated
~150 FSAs**



Driving Task Analysis



6) Define Entities, Events, Attributes, Resolutions, and Tolerances

CrossBuck(pos)
Lights(pos, state)
Crossing Gate(pos)
Signs(pos, facing-dir, text and graphics)
Tracks(pos, dir)
Train(pos, dir)
Lanes(pos, dir, width, curvature)
PassingZone(veh speeds, safety buffer, accel)
 eg. All attributes must be recognizable out to 600 to 800 feet

World Model
 Entities, Events, and Attributes

NoConstructionInPassZone
 NoTransitOrSchoolBusStopping
 NoPassZone-NotInEffect
 LaneMarkingsAllowPass
 NoIntersectionsInPassZone
 NoRailroadXInPassZone
 NoBridgeInPassZone
 NoTunnelInPassZone
 NoTollBothInPassZone

World Model
 Situation

LegalToPass

EnvironmentSafeToPass

SituationInFrontOKtoPass

SituationInBackOKtoPass

OnComingTrafficOKtoPass

Value Judgment

ConditionsGoodToPass

Plan

Behavior
 Generation



Analysis of knowledge requirements

Knowledge of geometry and dynamics

where are things?

where are they going?

what size, shape, feel?

what relationships to other things?

Knowledge of class membership

what are things?

what are their characteristics?

how can they be expected to behave?



Image processing requirements



A LADAR intensity image of cars in parking lot

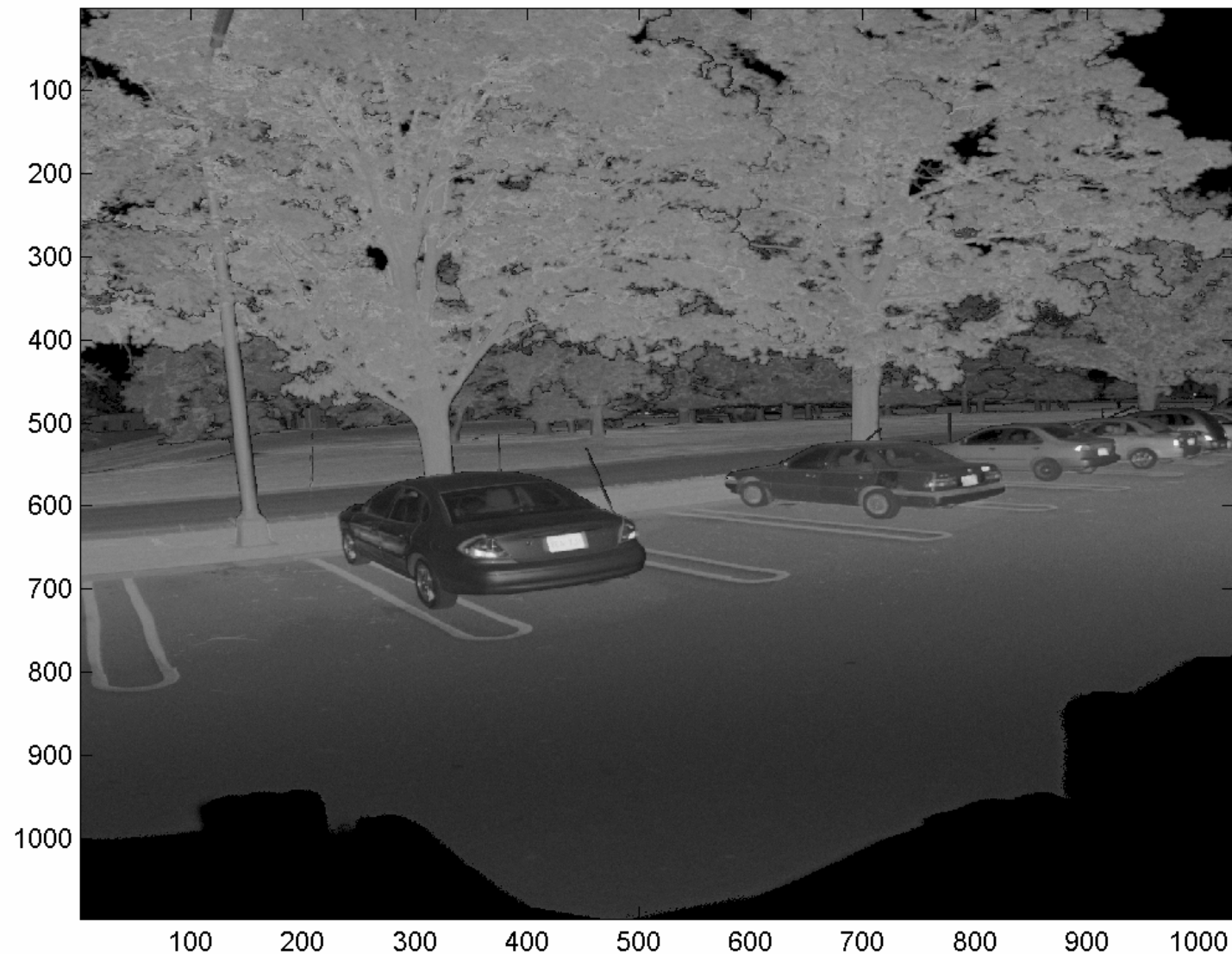




Image processing requirements



Segment object of interest

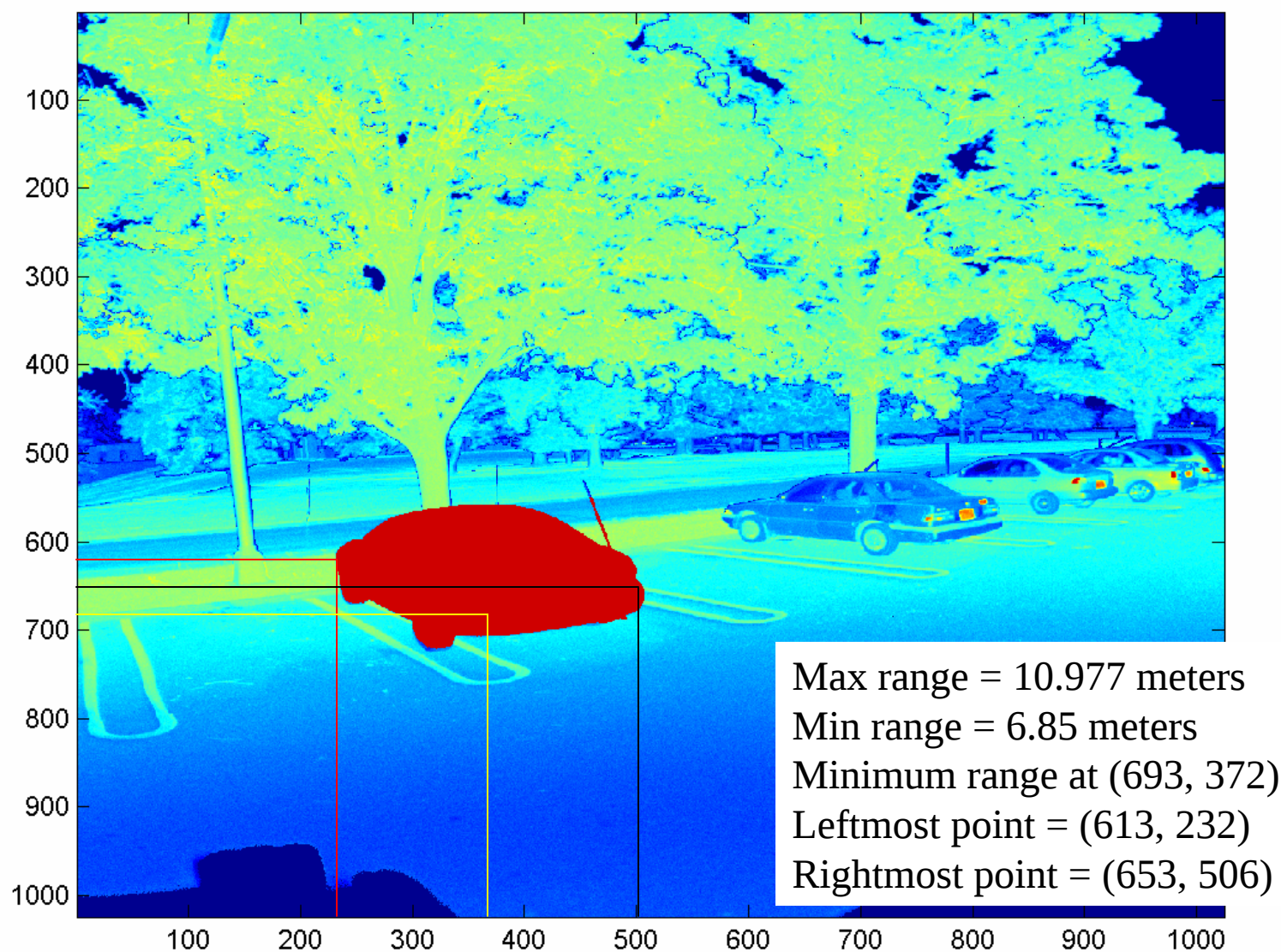




Image processing requirements



Objects on a virtual road

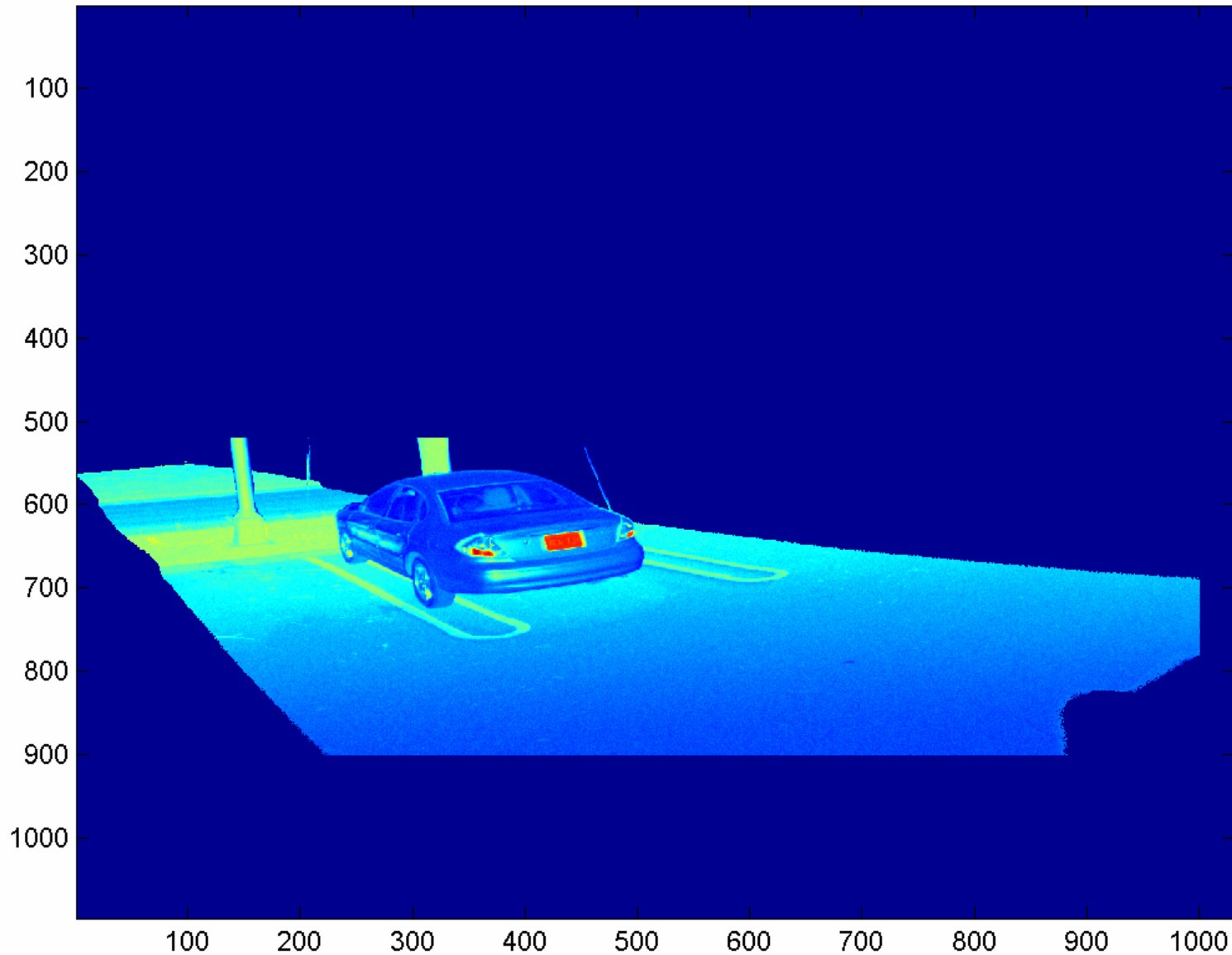




Image processing requirements



Segmented objects on virtual road

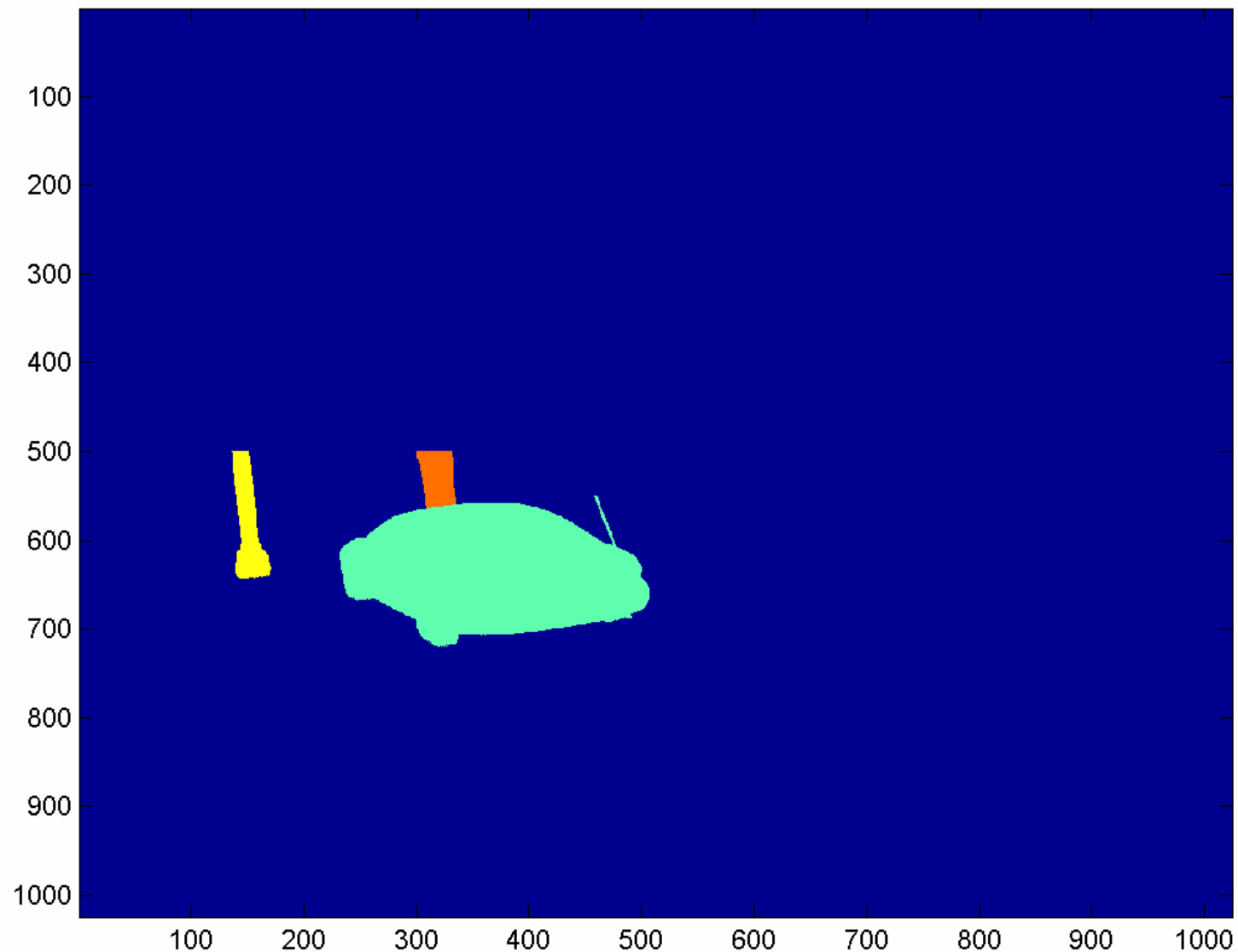
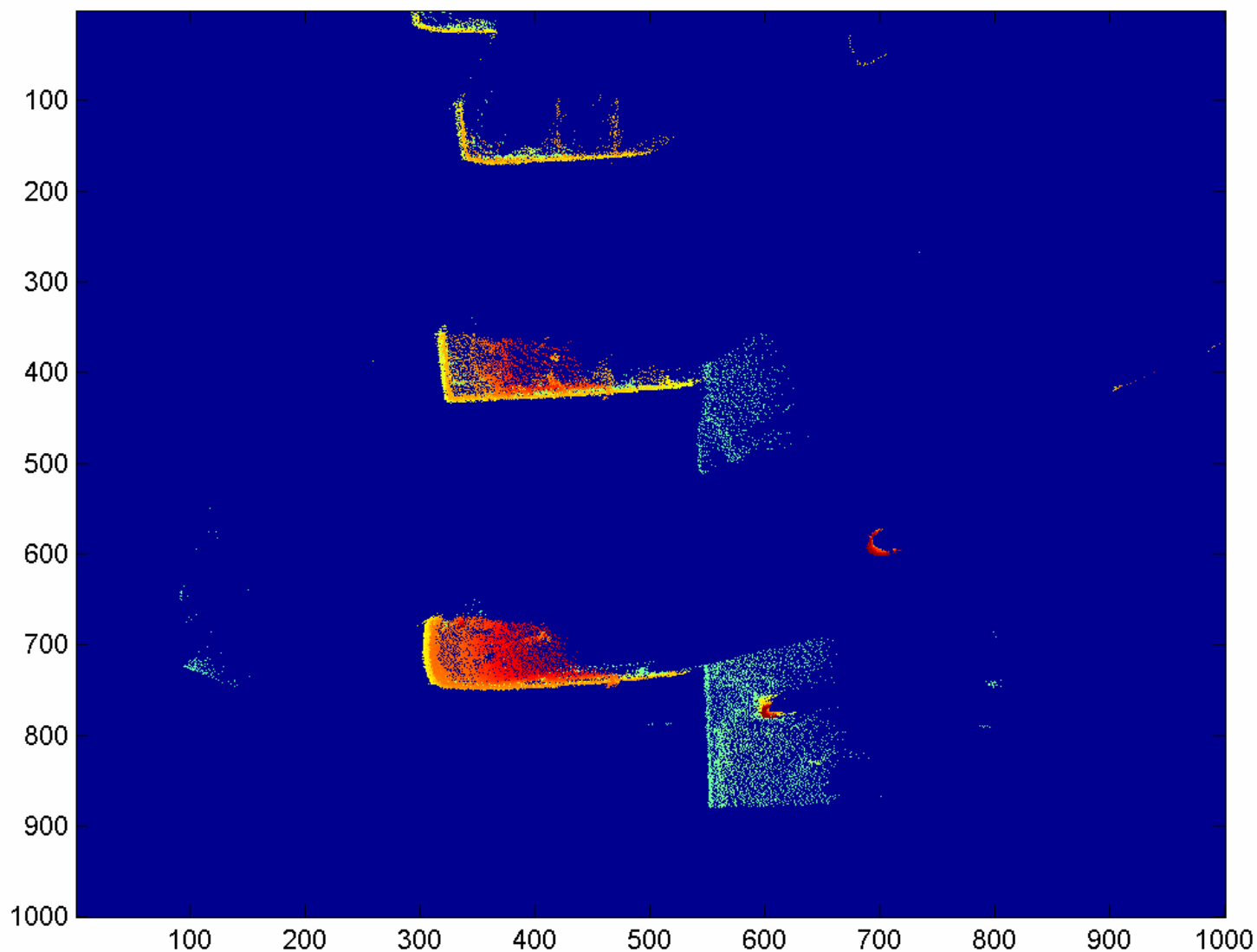




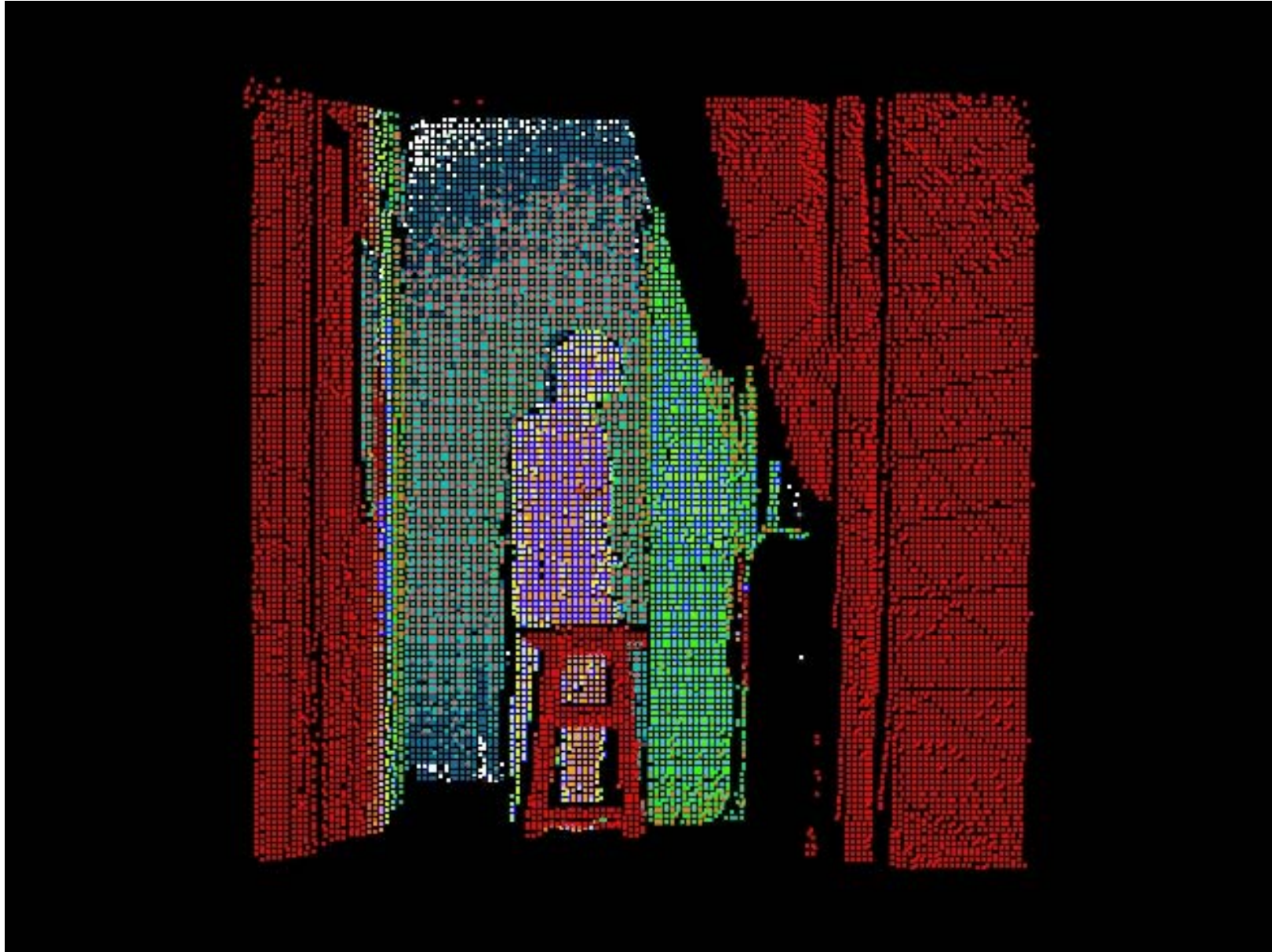
Image processing requirements



Map View of Cars Segmented from Pavement



Flash LADAR 128 x 128 range pixels

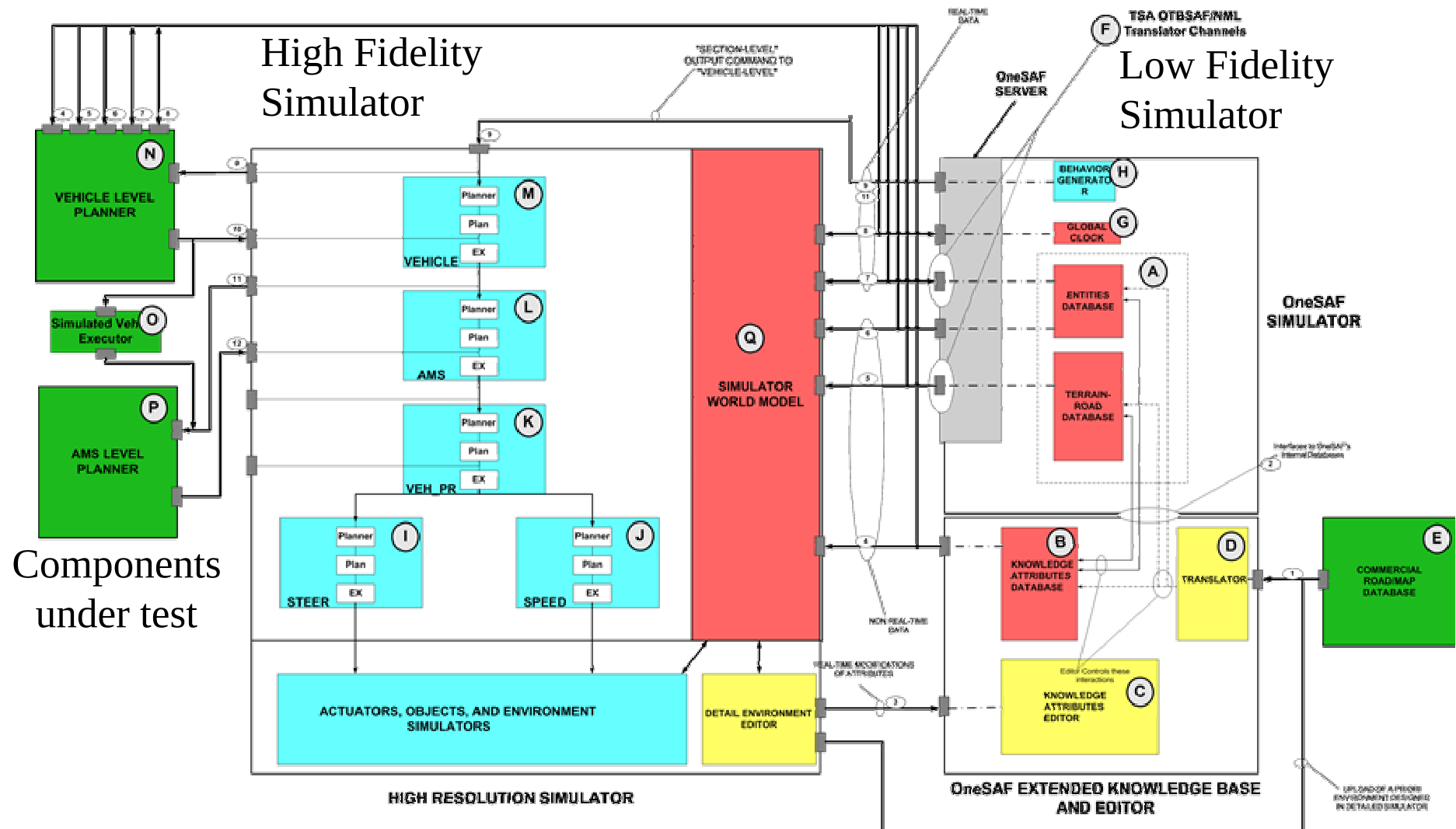


Flash LADAR 128 x 128 range pixels





Real/Virtual Environment for Software Development



Measures as Specifications

Performance requirements => performance measures

Performance measures => design specifications

Design specifications => technology requirements

Technology requirements => research goals

Example

Performance requirement = pass on two lane road

**Performance measures = accelerations, clearance,
perception range, accuracy, & latency**

**Design specs = sensor range, resolution, algorithms
for perception & control, computing power**

**Technology requirements = LADAR specs, camera
technology, INS/GPS, computing hardware**

Research goals = lasers, detectors, speeds, materials

Example 2

Performance requirement = enter thru hole in ceiling

Performance measures = dimensions, speed, mobility, mapping, target detection, operator workload

Design specs = vehicle performance, sensor specs, perception & control, computing power

Technology requirements = tether control, camera technology, 3-D localization and mapping

Research goals = cable dynamics, kinematics, materials, image registration

Summary and Conclusions

We have begun to move from theory to experiment

Several major experiments have been accomplished

Performance measures are being developed

Performance measures are driving specifications

Specifications are driving technology development