Institute of Navigation GNSS 2011 Conference
U.S. States and Local Government Subcommittee Session
Inertially-Aided Post-Processed Kinematic GNSS for Nautical Charting
September 19, 2011

DAVID EVANS AND ASSOCIATES INC.

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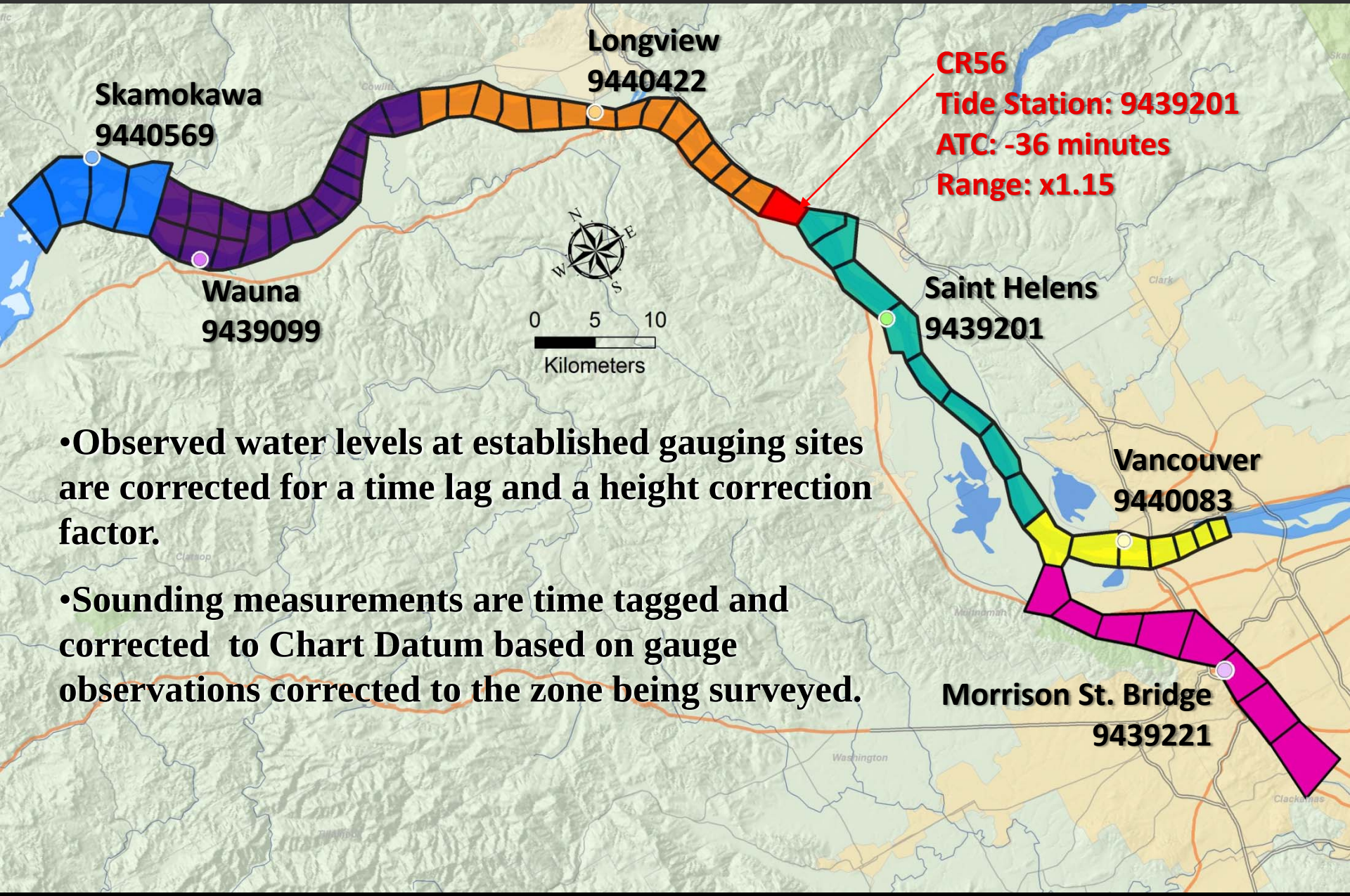
David Evans and Associates, Inc.
Marine Services Division

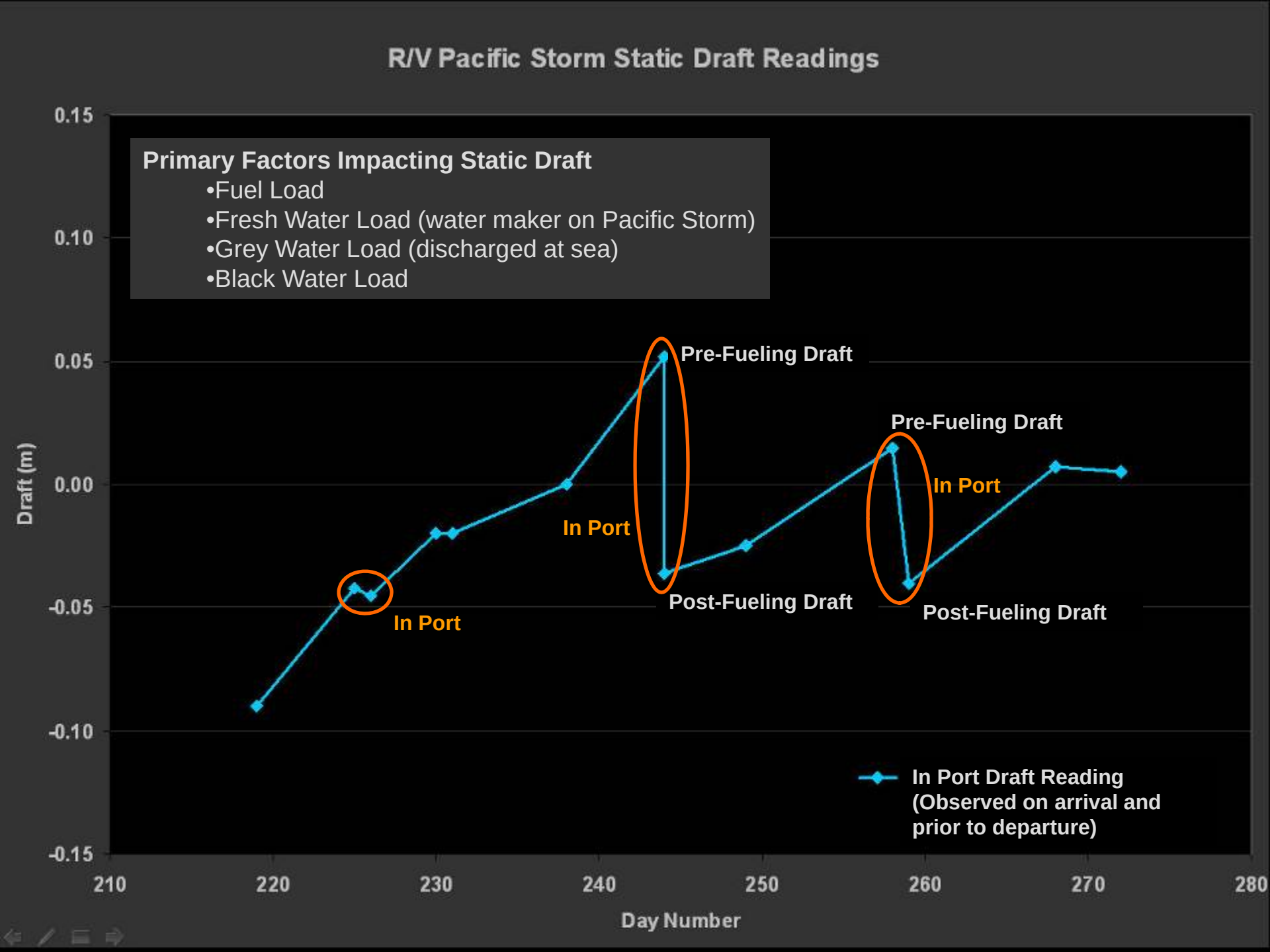
Factors Contributing to Vertical Errors in Hydrography

- Tidal Zoning (modeled water levels at survey vessel)
- Vessel Static Draft (changes in vessel loading)
- Vessel Dynamic Draft (changes in vessel speed)
- Long Period Heave (inertial systems unable to measure)

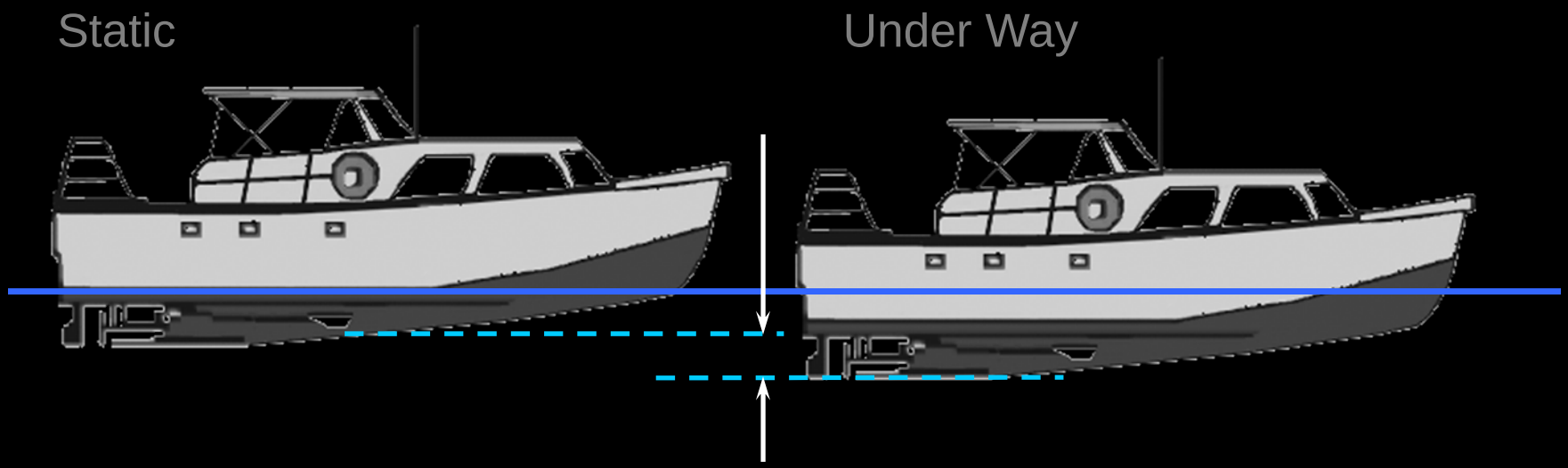
Columbia River Discrete Zoning



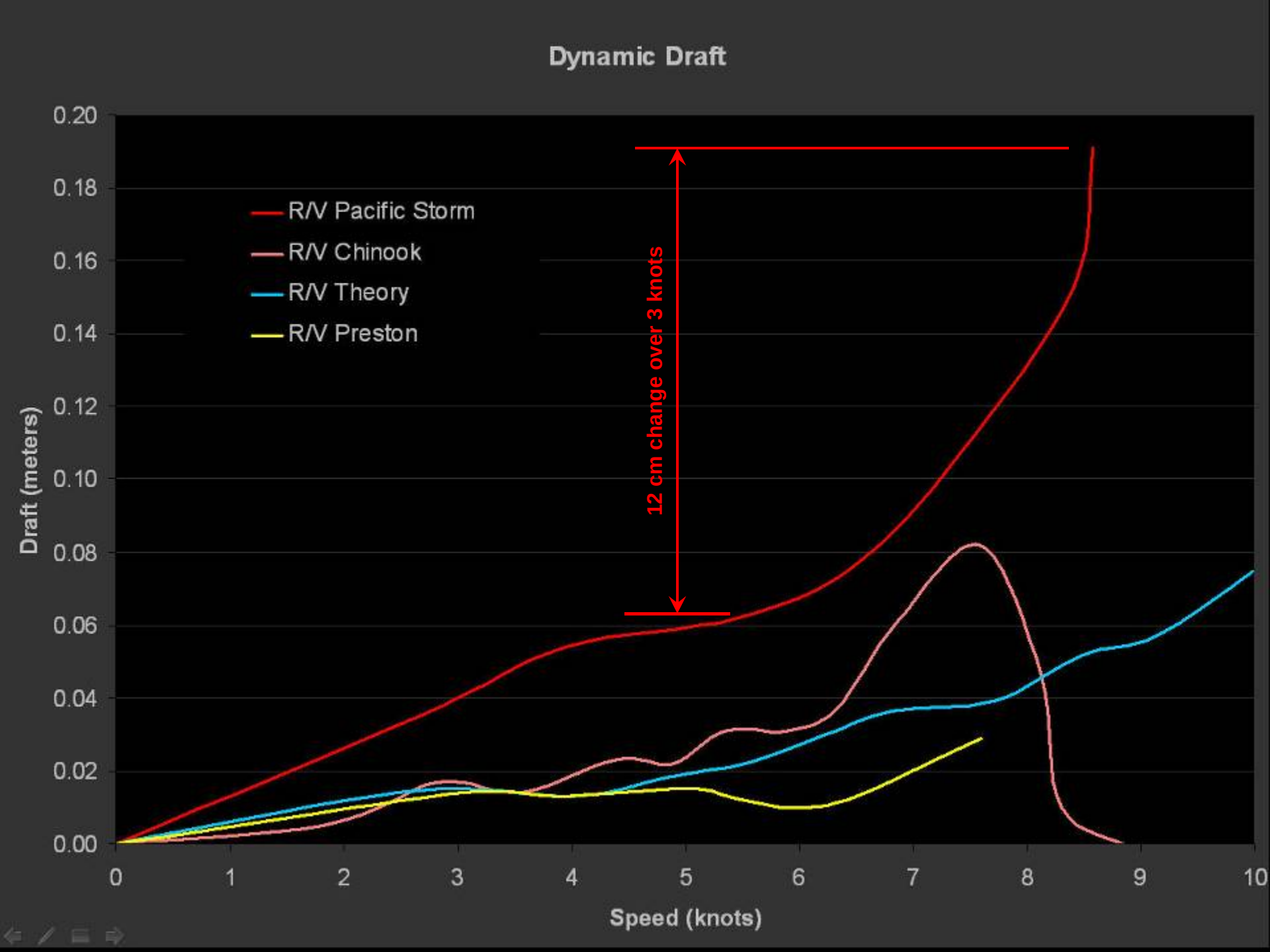
- Observed water levels at established gauging sites are corrected for a time lag and a height correction factor.
- Sounding measurements are time tagged and corrected to Chart Datum based on gauge observations corrected to the zone being surveyed.


R/V Pacific Storm Static Draft Readings
Primary Factors Impacting Static Draft
•Fuel Load
•Fresh Water Load (water maker on Pacific Storm)
•Grey Water Load (discharged at sea)
•Black Water Load
Pre-Fueling Draft
Pre-Fueling Draft
In Port
In Port
In Port
Post-Fueling Draft
Post-Fueling Draft
In Port Draft Reading (Observed on arrival and prior to departure)
Draft (m)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
210
220
230
240
250
260
270
280
Day Number

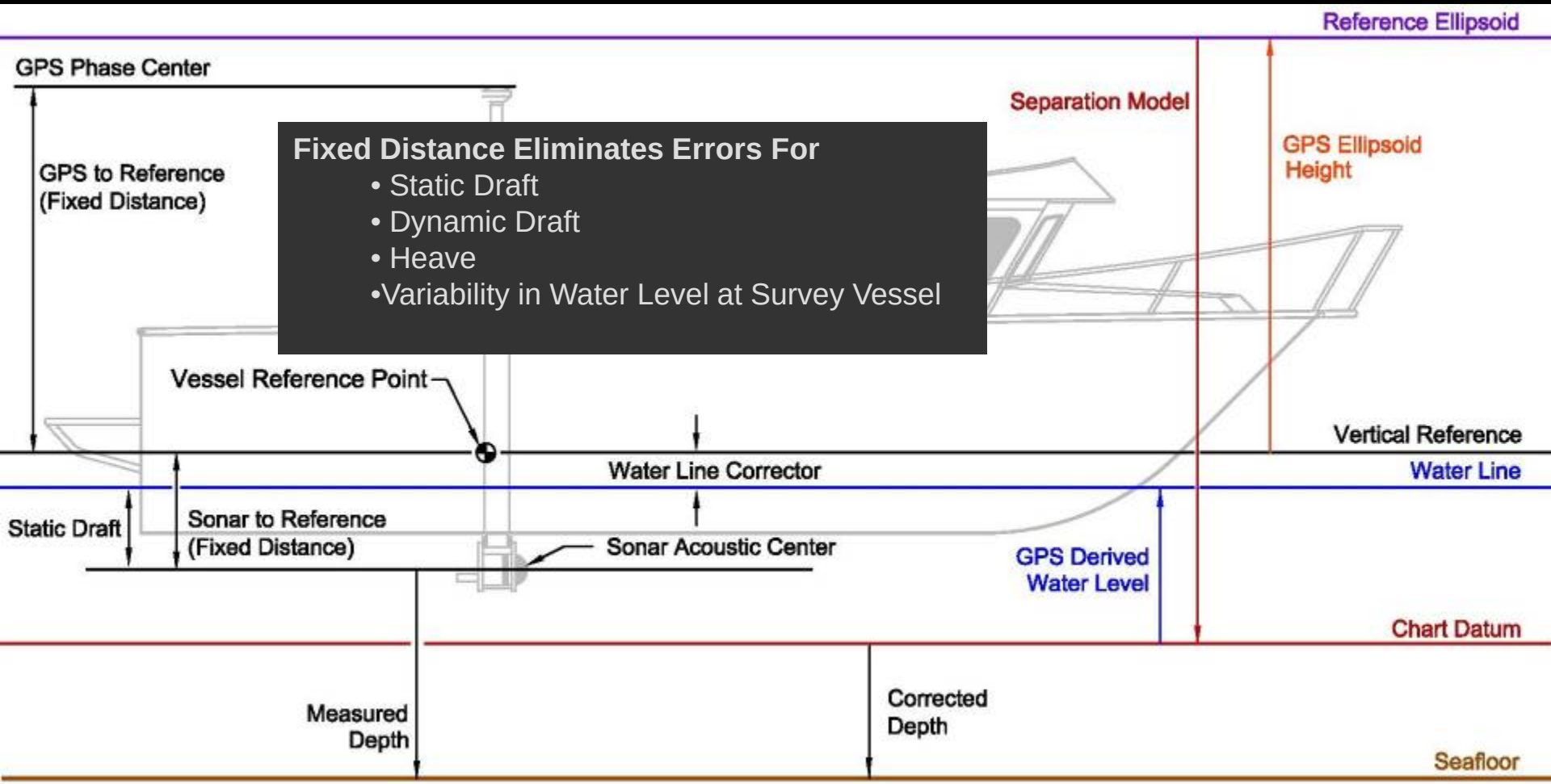
Dynamic Draft Corrections



Settlement - The effect of moving the hull through the water causes a local depression in the water surface around the hull. Typically corrected by tables relative to speed over ground. In the Columbia River this can result in significant errors when running into or with a 2 knot current (4 knot speed change). This correction is measured directly with GPS, eliminating speed over ground application errors.


Dynamic Draft
R/V Pacific Storm
R/V Chinook
R/V Theory
R/V Preston
12 cm change over 3 knots
Draft (meters)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
1
2
3
4
5
6
7
8
9
10
Speed (knots)

Vertical Components of Inertially-Aided GNSS Hydrographic Surveying



Water Level = Ellipsoid Height – Separation – Water Line Corrector

Inertially-Aided GNSS Derived Water Levels

- Applanix POS MV 320
- Processing Computer (PCS)
- Inertial Measurement Unit (IMU)
- Two Dual Frequency GNSS Antennas

Provides Vessel

- Position
- Heading
- Heave/Pitch/Roll
- Quality metrics

Inertially-Aided Real Time Kinematic (RTK)

- Advantages
  - Provides real-time water levels that can be used for color swath coverage relative to chart datum
  - Provides real-time kinematic GNSS quality control
  - Seamless swath coverage in real-time for improved quality control and quality assurance for bathymetric data
- Disadvantages
  - Shore Support needed for base stations and radio link
  - Radio link can be problematic in some areas and may result in rejection of the survey if significant loss of corrections is encountered that can not be corrected with the strap down inertial system
  - Range from base station is limited by radio link or 20 km

Inertially-Aided Post-Processed Kinematic (PPK)

- Post-processed tightly coupled inertial and GNSS data through Applanix POSPac MMS software
  - Computes time stamped Smoothed Best Estimate Trajectory (SBET) files through forward and reverse processing of data
- Advantages
  - Eliminates need for radio link
  - Distance from base can be extended up to 20 km using a single base
  - SmartBase solution allows for extended range from base stations
  - Improved accuracy over GPS outages from forward/backward smoothing
- Disadvantages
  - Real-time water levels not available for inshore coverage evaluation or quality control of GPS and bathymetric data
  - Range from base station is limited to 20 km for SingleBase solution
  - Potential for decreased accuracy with SmartBase solution

SmartBASE Processing

Download Base Stations

↓

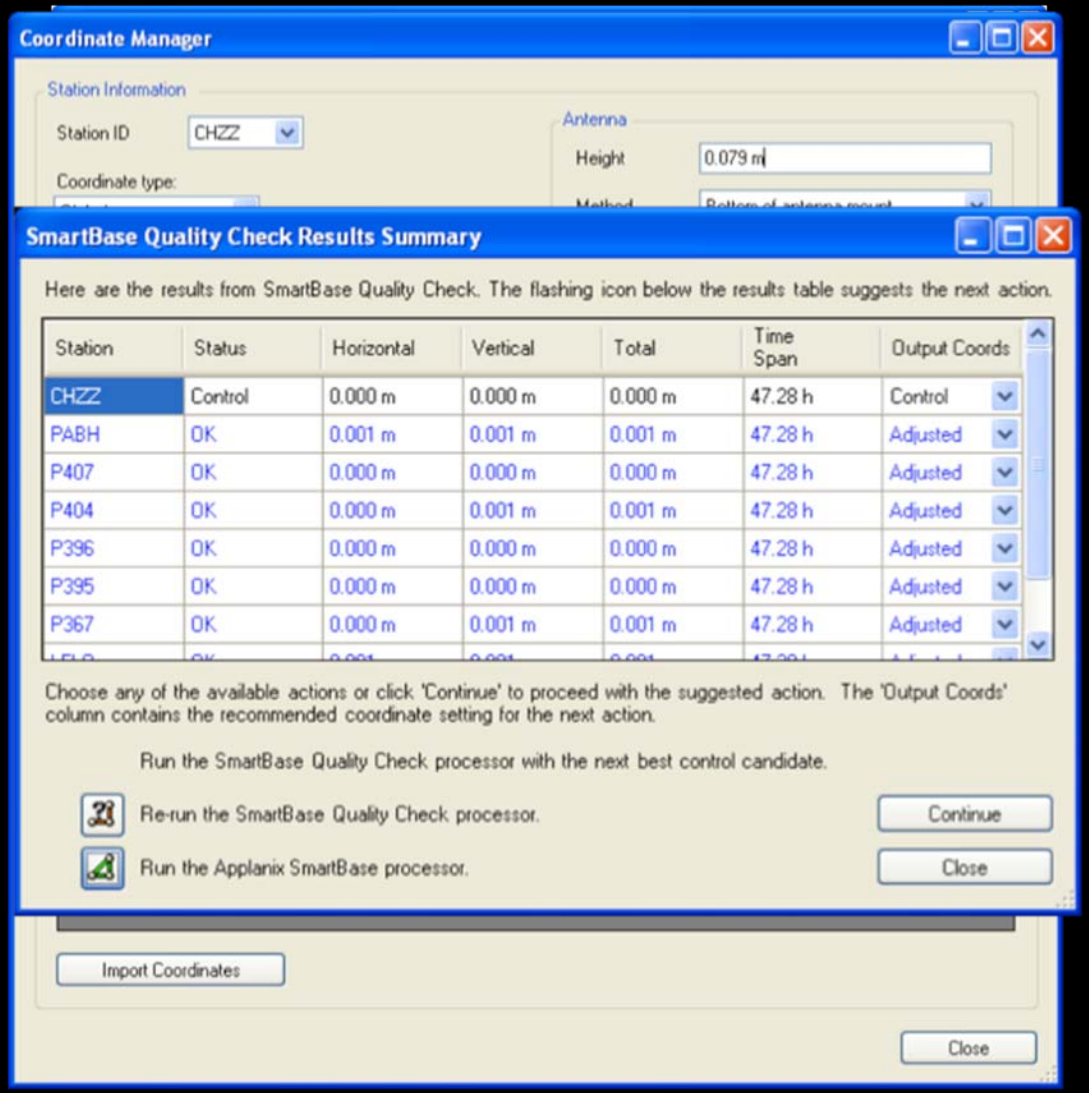
Set Base Stations to NAD83

↓

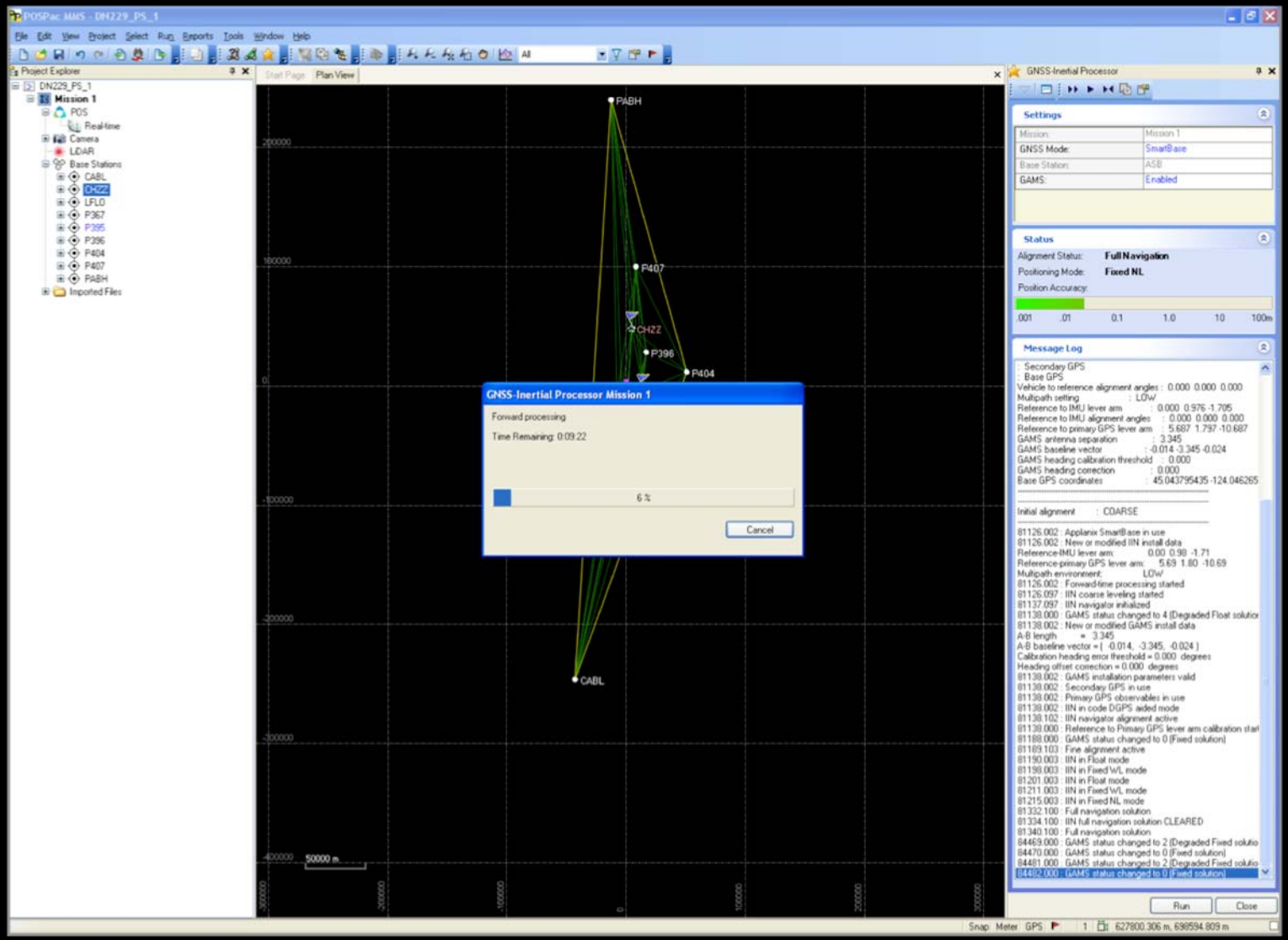
Quality Check Stations

↓

Generate Corrections



Tightly Coupled Inertially-Aided GNSS Processing



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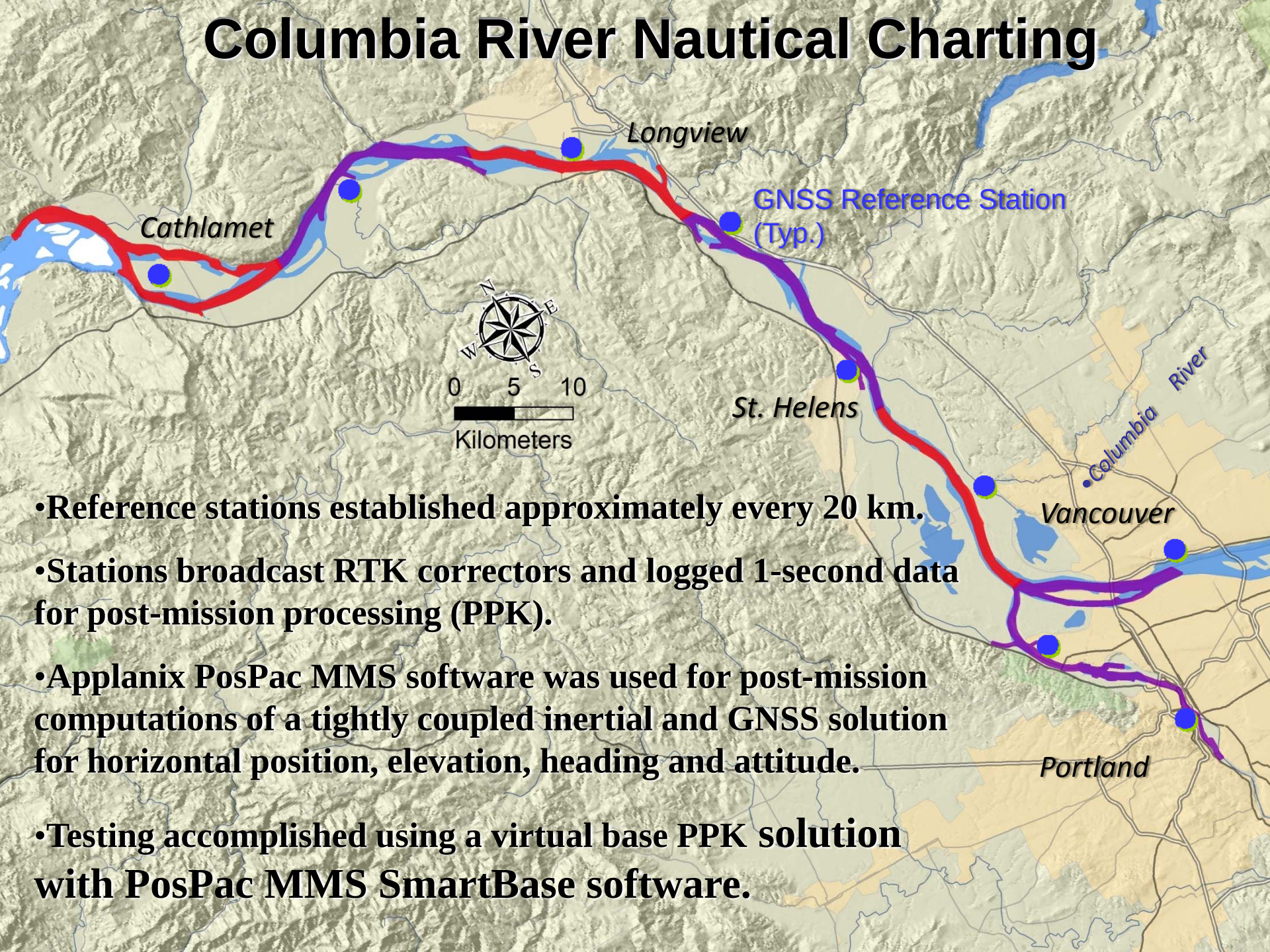
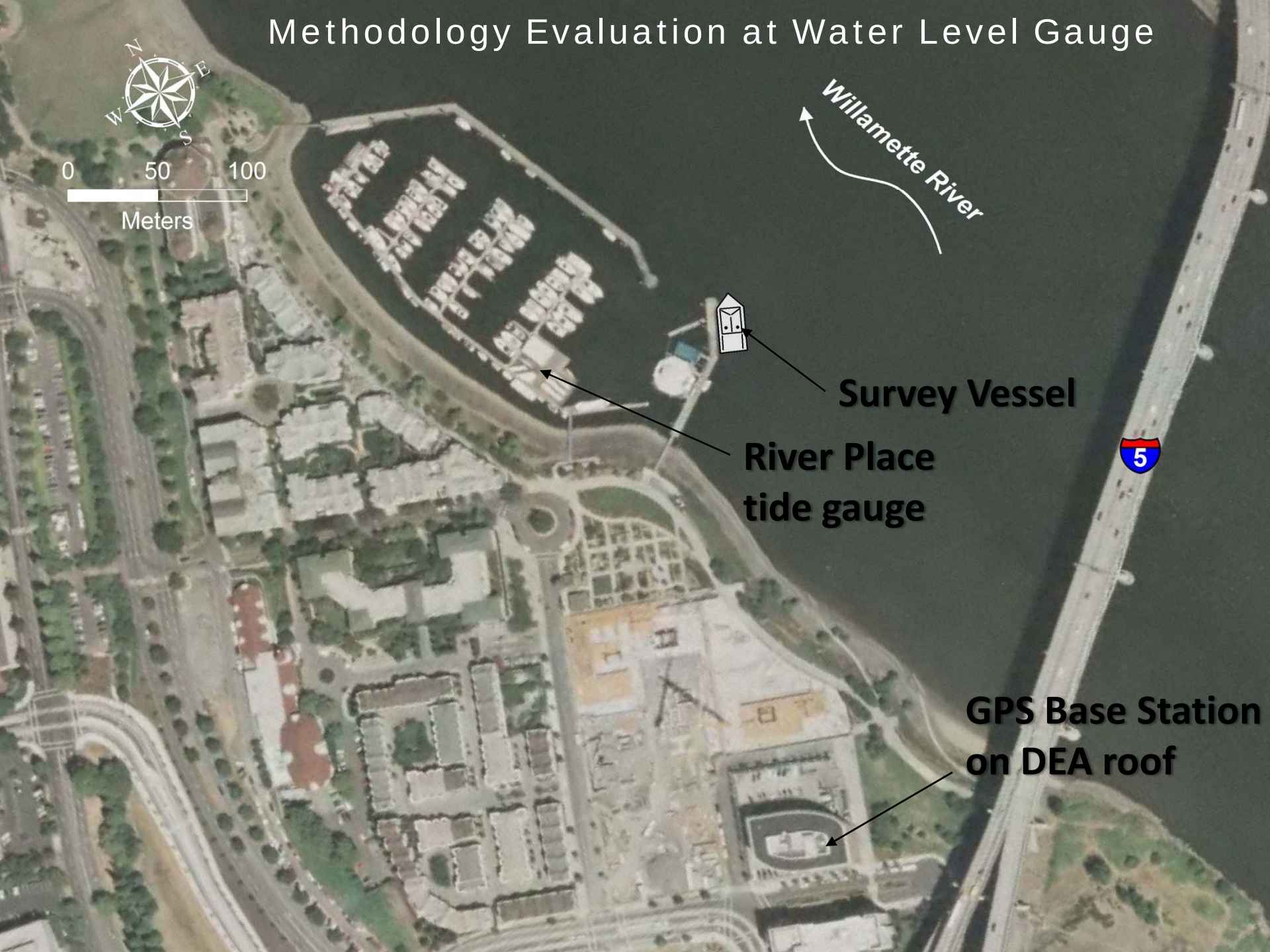
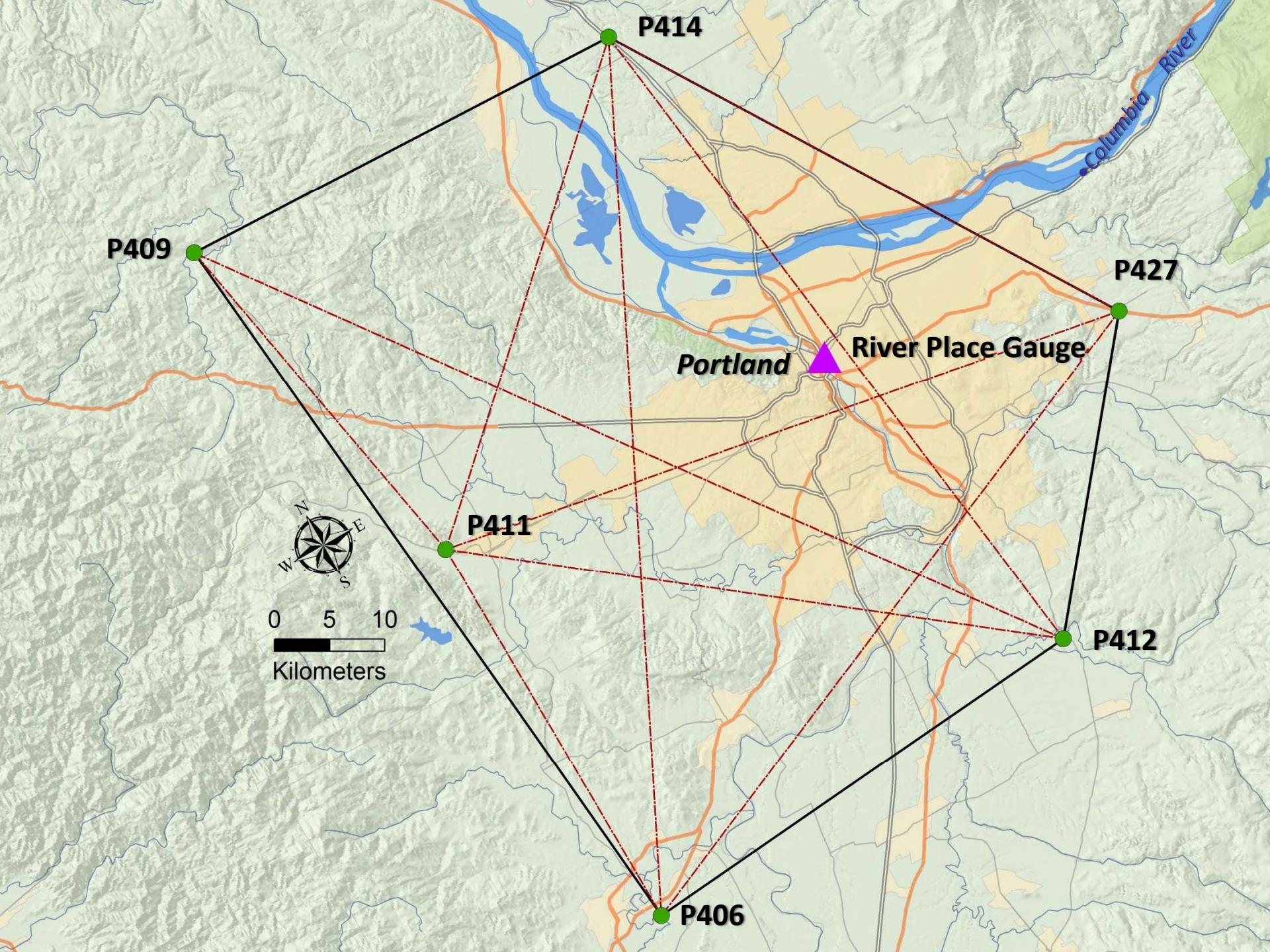
Columbia River Nautical Charting

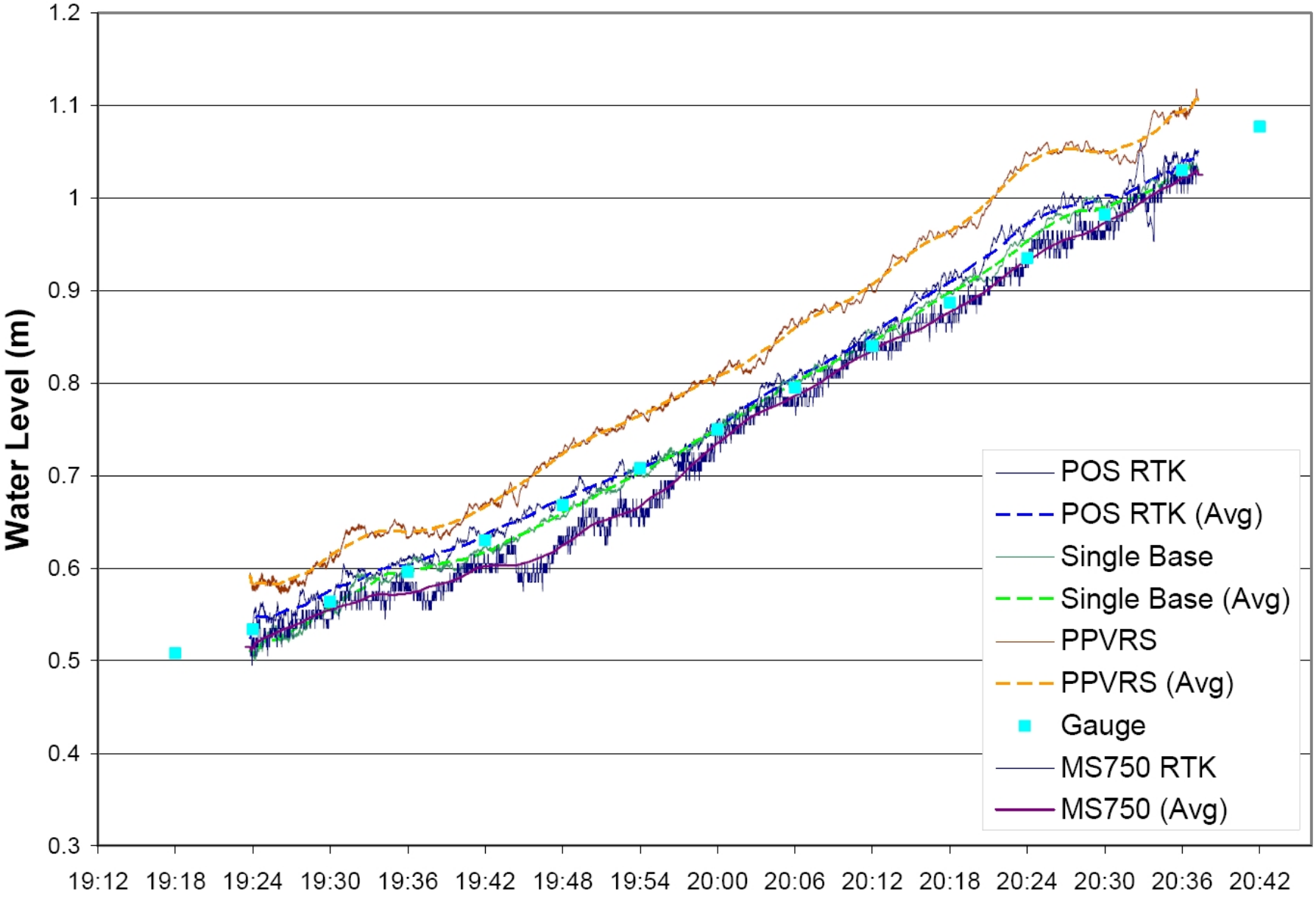


- **Reference stations established approximately every 20 km.**
- **Stations broadcast RTK correctors and logged 1-second data for post-mission processing (PPK).**
- **Applanix PosPac MMS software was used for post-mission computations of a tightly coupled inertial and GNSS solution for horizontal position, elevation, heading and attitude.**
- **Testing accomplished using a virtual base PPK solution with PosPac MMS SmartBase software.**


Methodology Evaluation at Water Level Gauge
N
E
S
W
0
50
100
Meters
Willamette River
Survey Vessel
River Place
tide gauge
5
GPS Base Station
on DEA roof


P414
P409
P427
Columbia River
Portland
River Place Gauge
P411
P412
P406
N
E
S
W
0 5 10
Kilometers

Inertially-Aided GNSS Compared to Gauge Observations

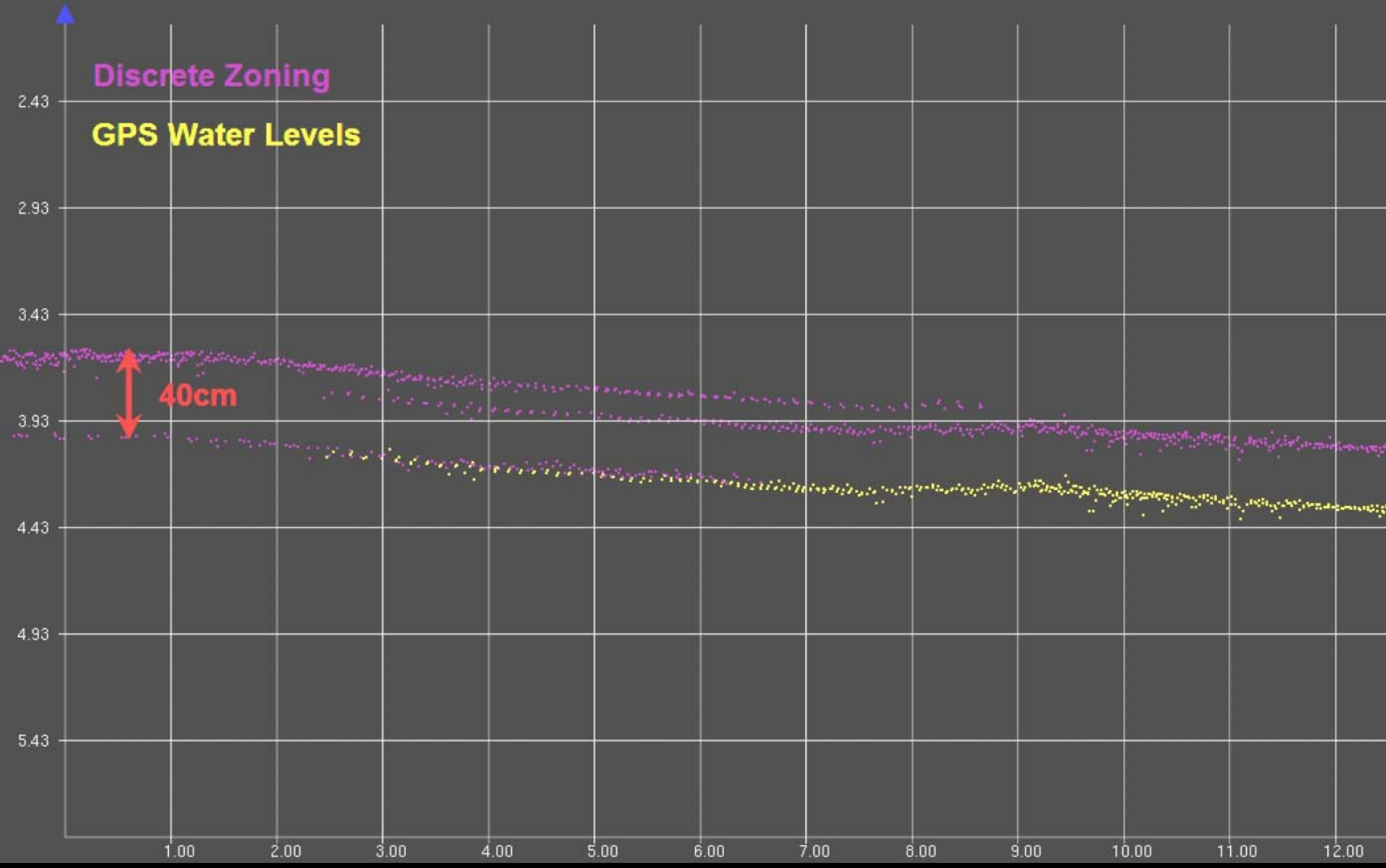


Inertially-Aided GNSS Compared to Gauge Observations

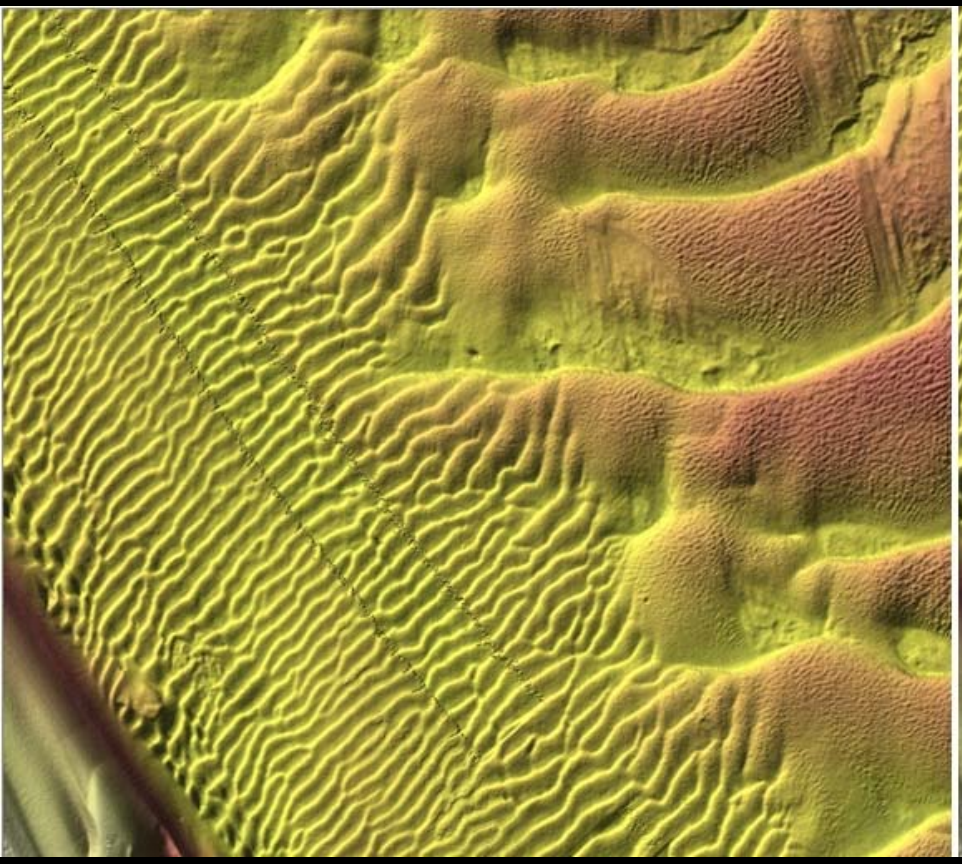
		POS RTK		POS Single Base		POS PPVRS		MS750	
	Gauge	Average	*Delta*	Average	*Delta*	Average	*Delta*	Average	*Delta*
19:24	0.534	0.541	*-0.007*	0.508	*0.026*	0.582	*-0.048*	0.514	*0.020*
19:30	0.564	0.576	*-0.012*	0.557	*0.007*	0.614	*-0.050*	0.555	*0.009*
19:36	0.596	0.604	*-0.008*	0.597	*-0.001*	0.639	*-0.043*	0.573	*0.023*
19:42	0.630	0.636	*-0.006*	0.617	*0.013*	0.666	*-0.036*	0.602	*0.028*
19:48	0.668	0.675	*-0.007*	0.660	*0.008*	0.724	*-0.056*	0.625	*0.043*
19:54	0.708	0.708	*0.000*	0.704	*0.004*	0.765	*-0.057*	0.667	*0.041*
20:00	0.750	0.751	*-0.001*	0.750	*0.000*	0.807	*-0.057*	0.735	*0.015*
20:06	0.795	0.807	*-0.012*	0.801	*-0.006*	0.860	*-0.065*	0.786	*0.009*
20:12	0.840	0.852	*-0.012*	0.845	*-0.005*	0.907	*-0.067*	0.835	*0.005*
20:18	0.887	0.909	*-0.022*	0.898	*-0.011*	0.965	*-0.078*	0.877	*0.010*
20:24	0.935	0.973	*-0.038*	0.954	*-0.019*	1.036	*-0.101*	0.933	*0.002*
20:30	0.982	1.003	*-0.021*	0.990	*-0.008*	1.049	*-0.067*	0.974	*0.008*
20:36	1.030	1.041	*-0.011*	1.029	*0.001*	1.094	*-0.064*	1.021	*0.009*
		Mean	***-0.012***		***0.001***		***-0.061***		***0.017***
		Median	***-0.011***		***0.000***		***-0.057***		***0.010***
		Std Dev	***0.010***		***0.011***		***0.017***		***0.013***

all values in meters

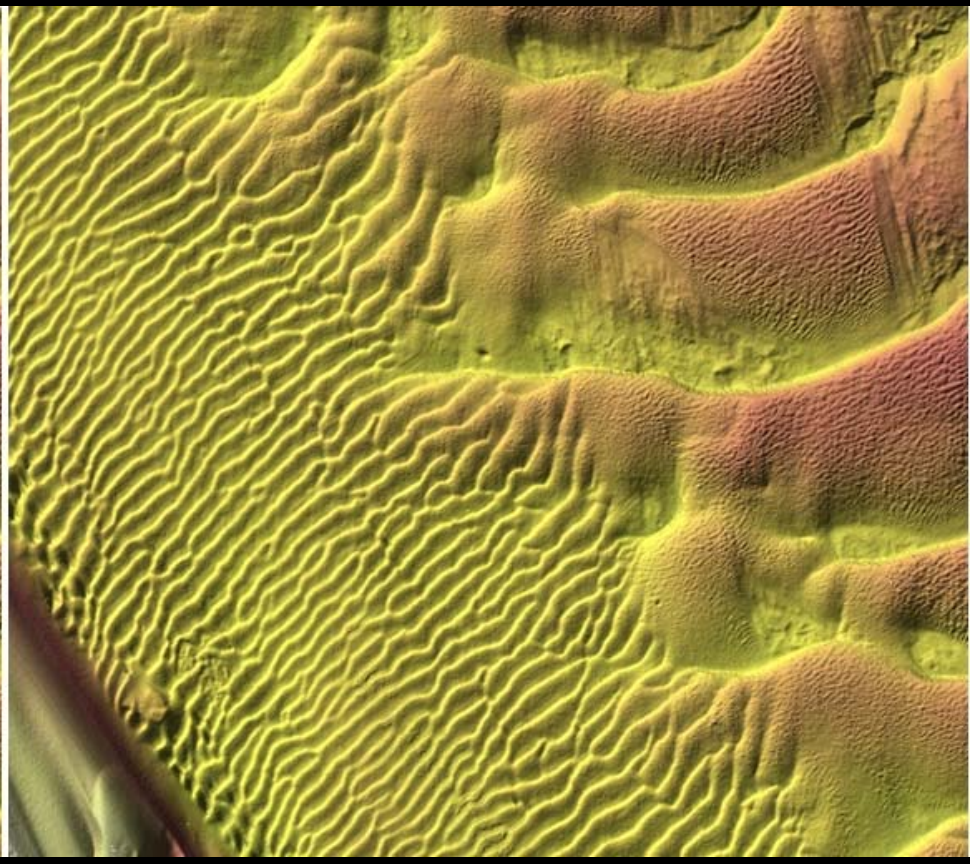
Discontinuities in Application of Discrete Zoning



Discontinuities in Discrete Zoning vs. GNSS



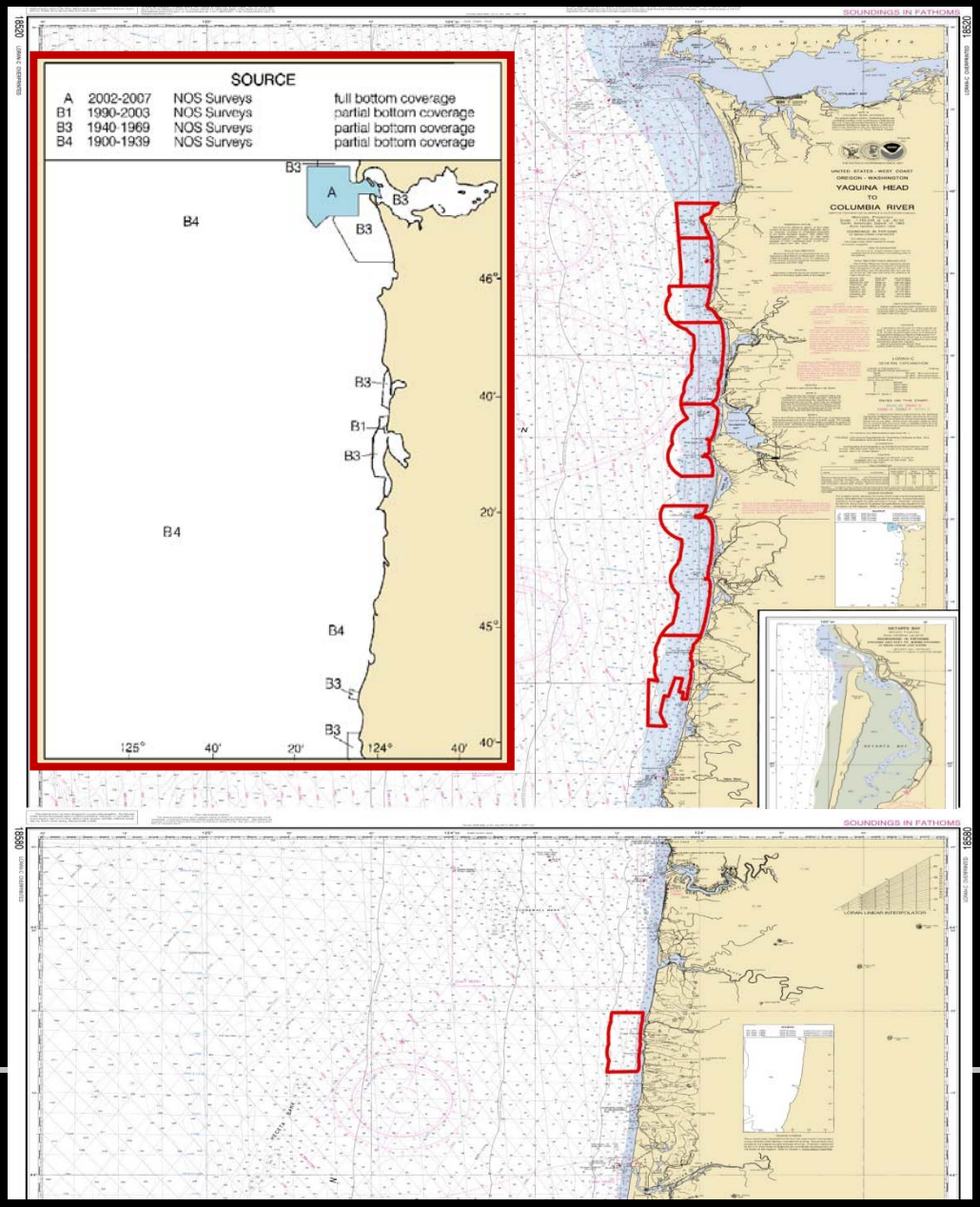
Zoned Tides



Inertially-Aided GNSS Tides

Oregon Coastal Mapping Project

- 8 Survey Sheets
- Columbia River to South of Newport, Oregon
- 2009-2010



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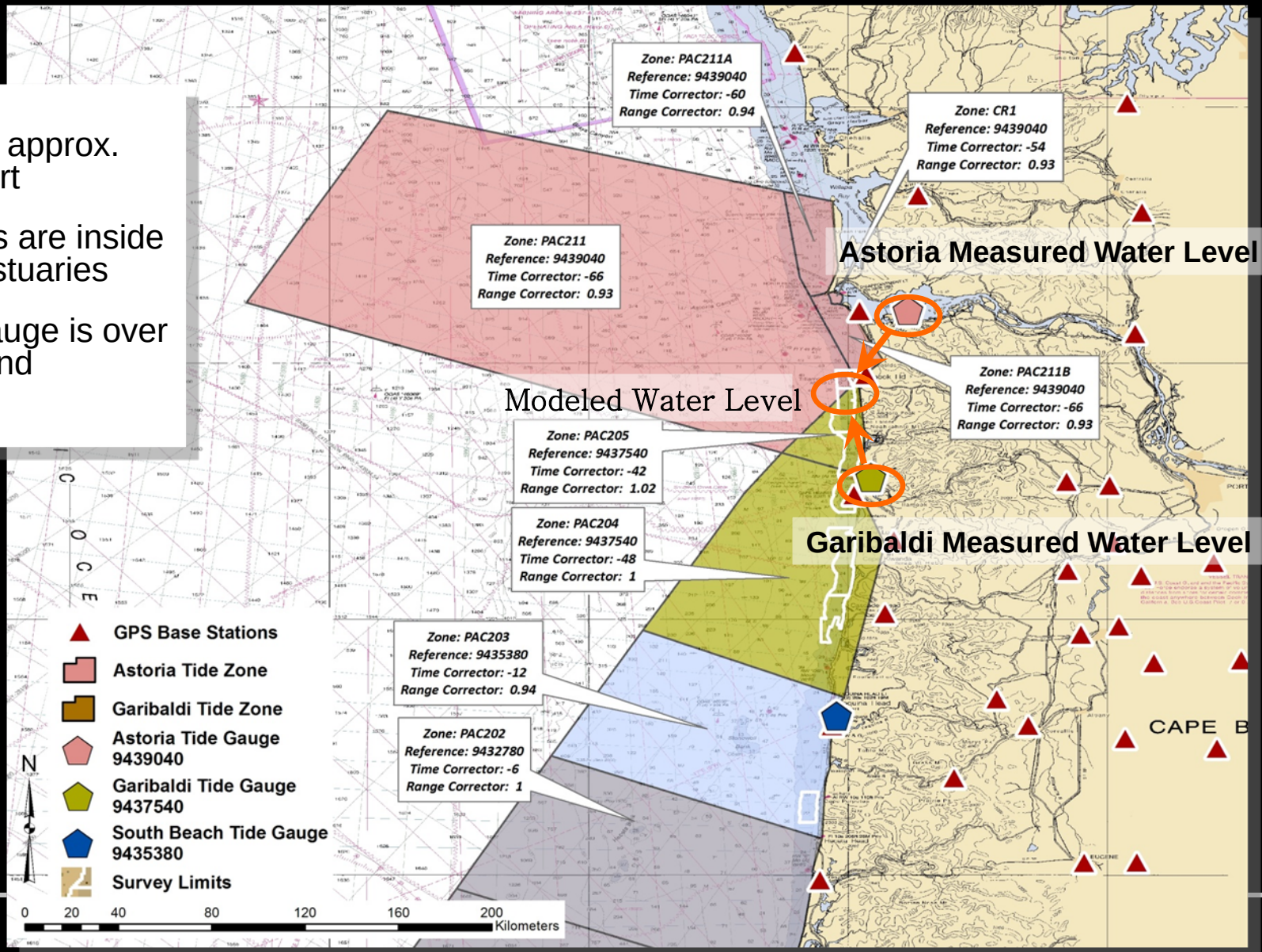
Approach to Oregon Coast Water Levels for Charting

- Application of inertially-aided GNSS derived water levels.
- MLLW modeled relative to NAD83 Ellipsoid heights using VDatum and GEOID 03.
- Utilized an Applanix SmartBASE solution from existing NGS CORS and SOPAC GPS reference stations.
- Verified methodology by logged GNSS derived water levels at South Beach NWLON site for comparison.
- Compared GNSS water levels relative to zoned water levels from NOAA Center for Operational Oceanographic Products and Services (CO-OPS) gauging stations.

Traditional Tide Zones & Gauges

- 3 Gauges approx. 50km apart
- All gauges are inside bays or estuaries
- Astoria gauge is over 30km inland



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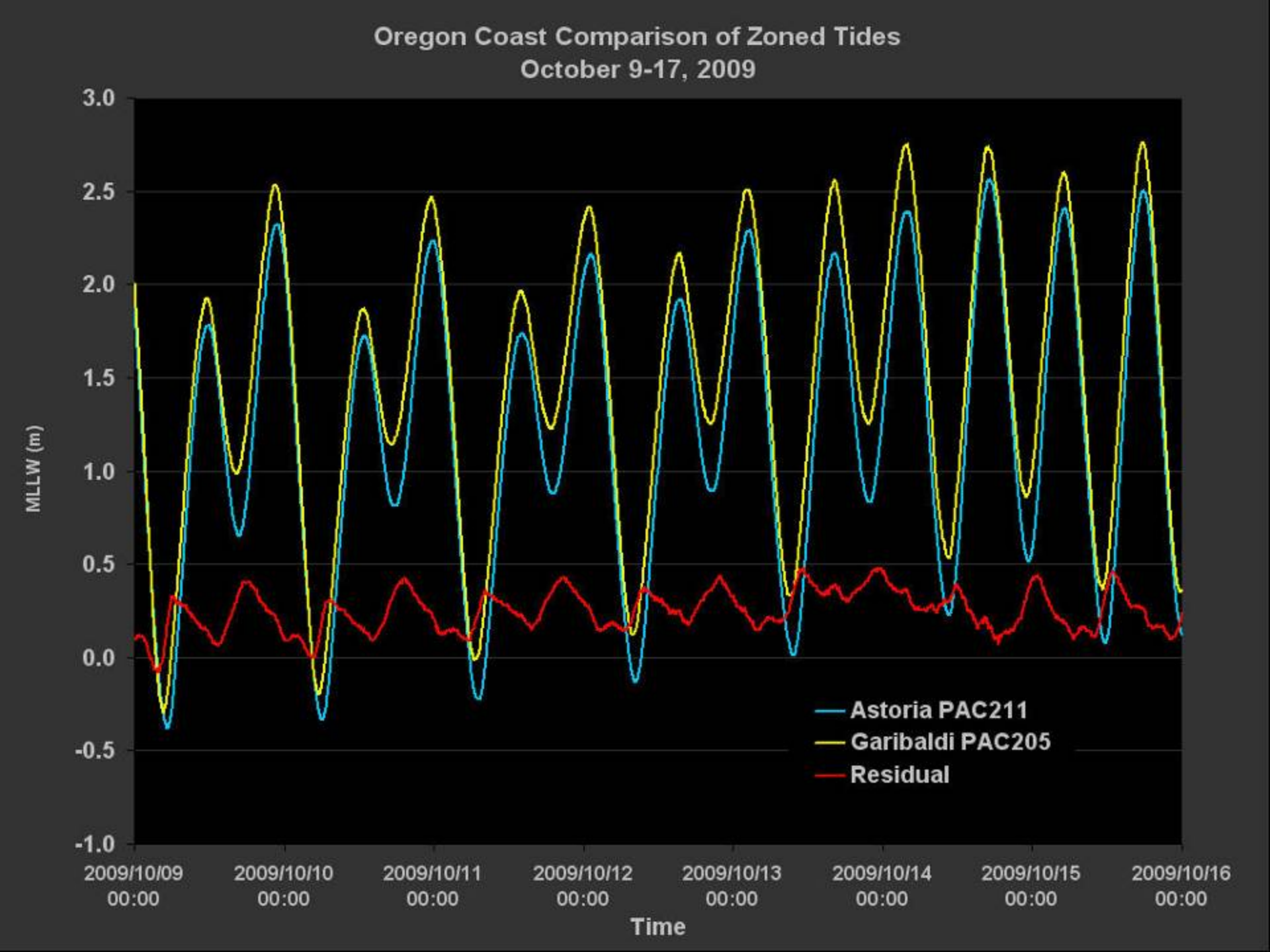
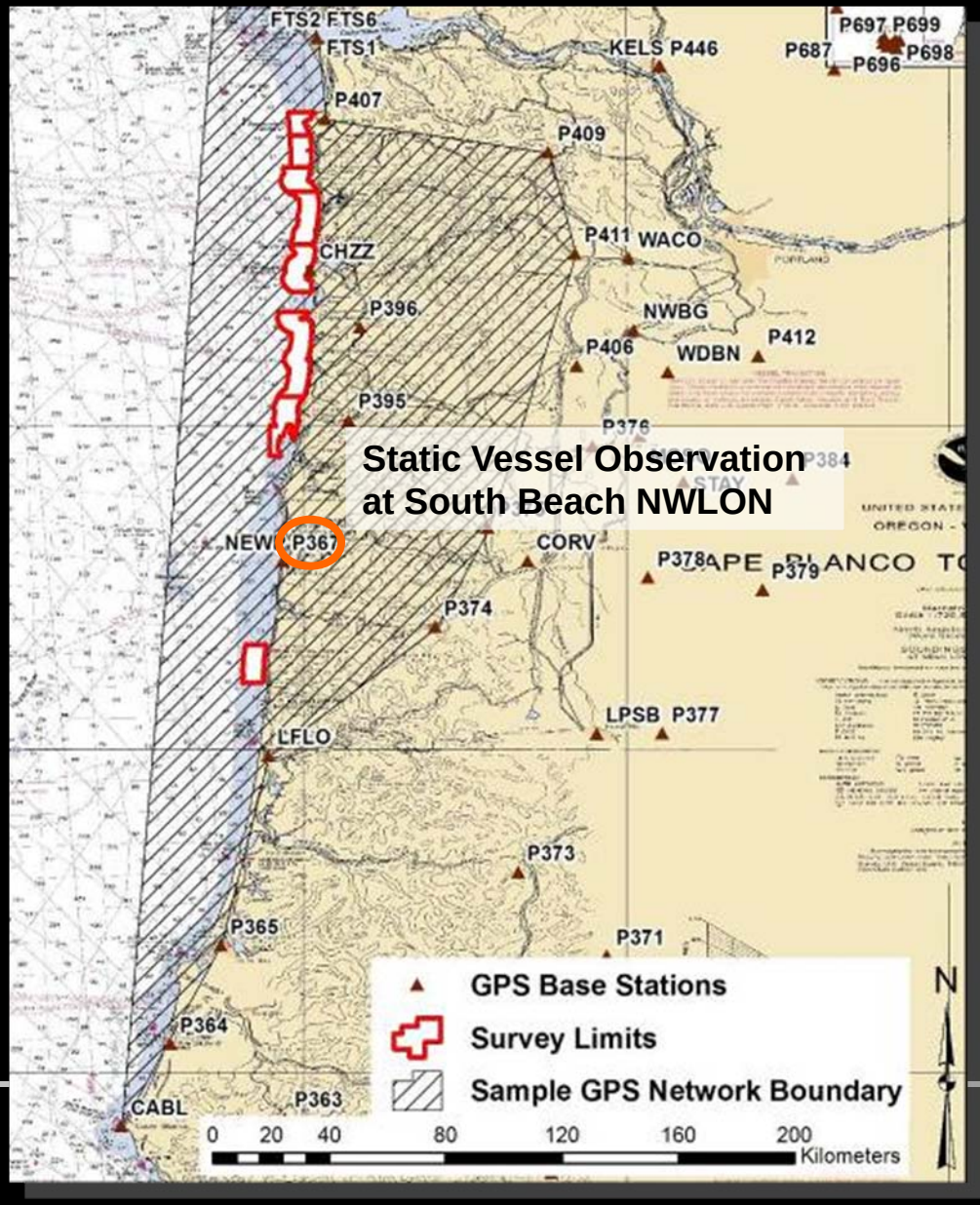

Oregon Coast Comparison of Zoned Tides
October 9-17, 2009
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
MLLW (m)
Astoria PAC211
Garibaldi PAC205
Residual
2009/10/09 00:00
2009/10/10 00:00
2009/10/11 00:00
2009/10/12 00:00
2009/10/13 00:00
2009/10/14 00:00
2009/10/15 00:00
2009/10/16 00:00
Time

GPS Stations & Network Boundary

- Continuously Operating Reference Stations
  - NGS CORS
  - SOPAC
  - Precise Ephemeris
- Applanix SmartBASE
  - Average of 10 Base Stations per Sheet
- Modified VDATUM Bin File Applied in CARIS
  - NAD83 to MLLW
  - GEOID 03



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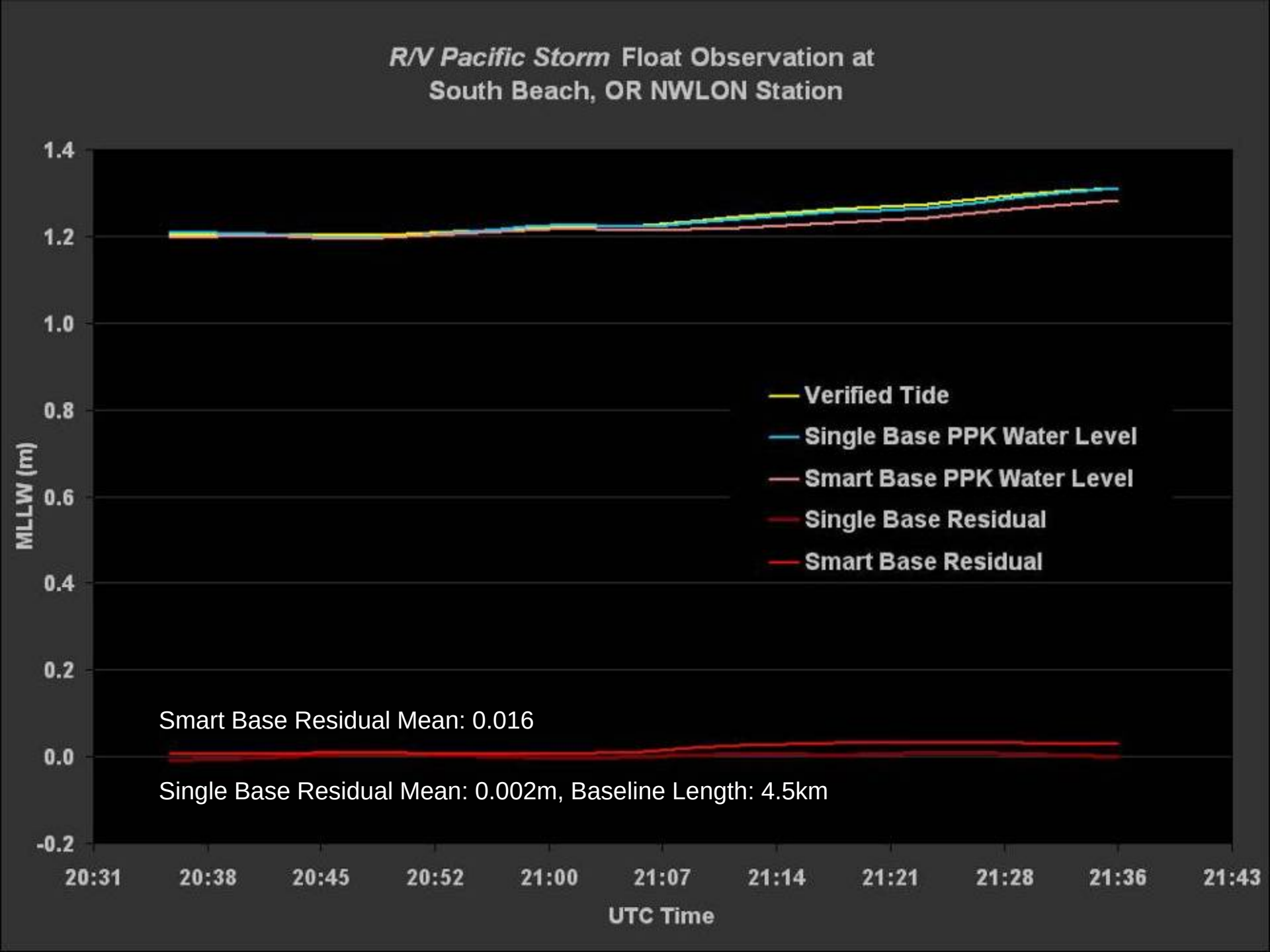
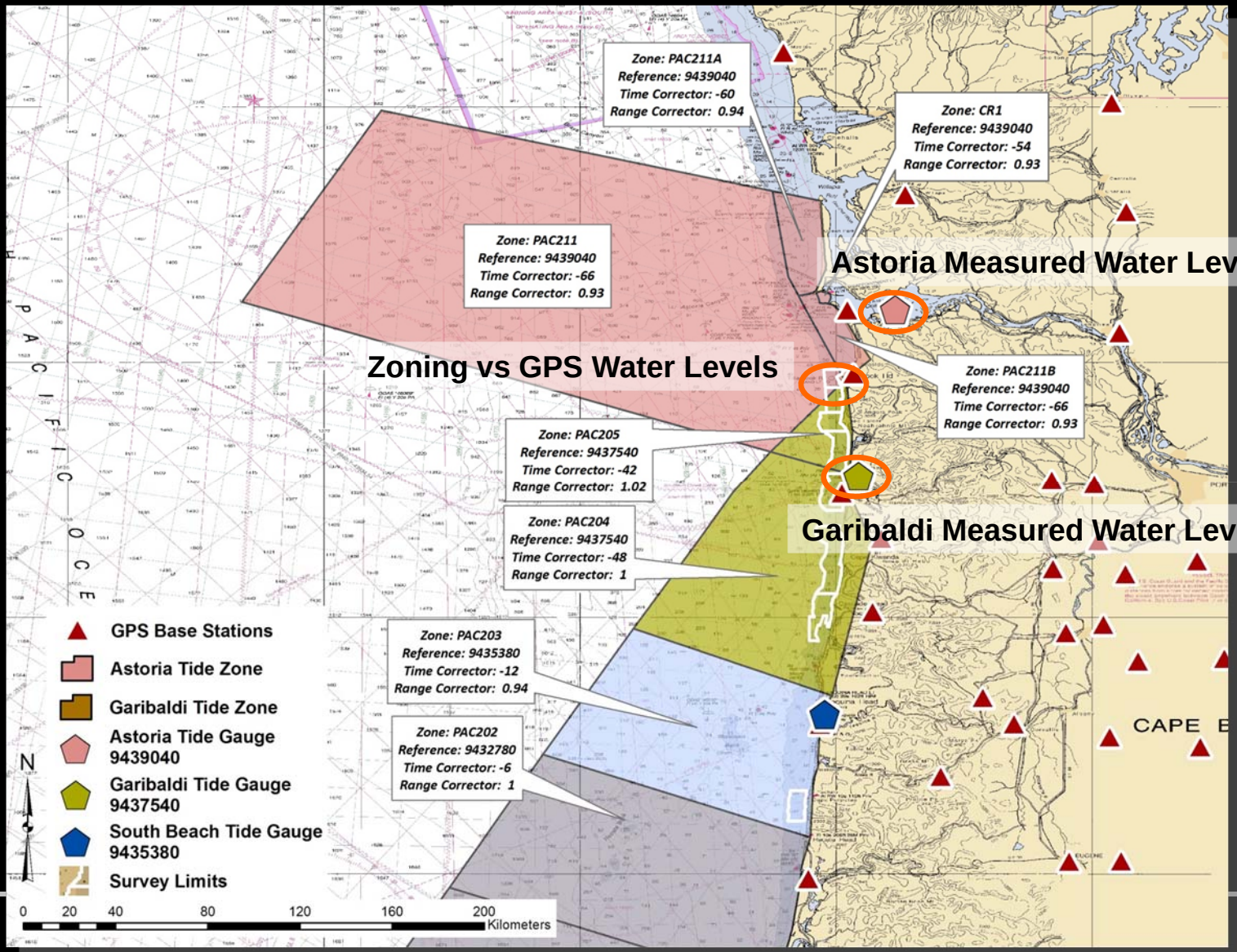

R/V Pacific Storm Float Observation at
South Beach, OR NWLON Station
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
MLLW (m)
Verified Tide
Single Base PPK Water Level
Smart Base PPK Water Level
Single Base Residual
Smart Base Residual
Smart Base Residual Mean: 0.016
Single Base Residual Mean: 0.002m, Baseline Length: 4.5km
20:31
20:38
20:45
20:52
21:00
21:07
21:14
21:21
21:28
21:36
21:43
UTC Time

Traditional Tide Zones & Gauges Compared to VDatum and GPS



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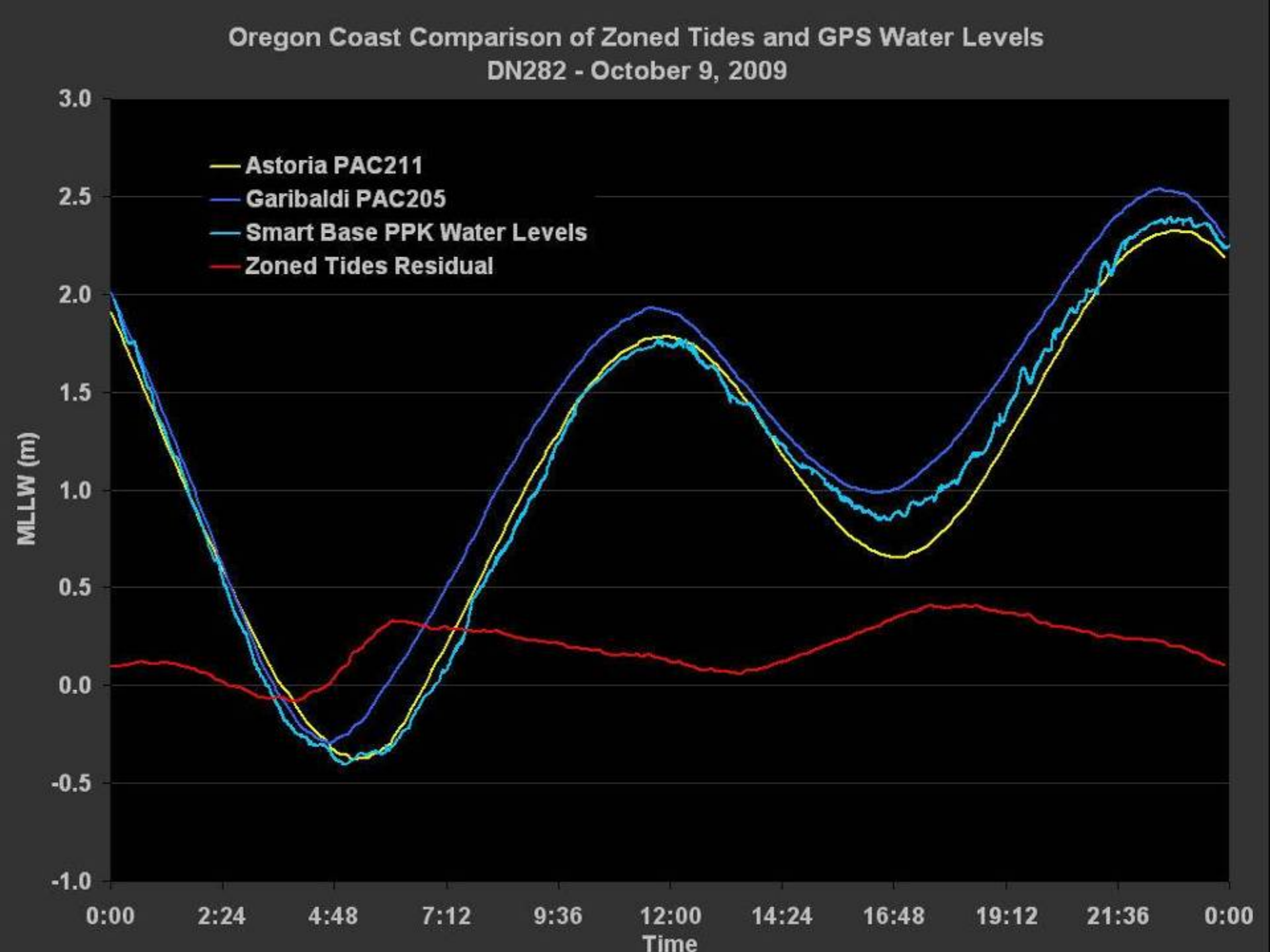
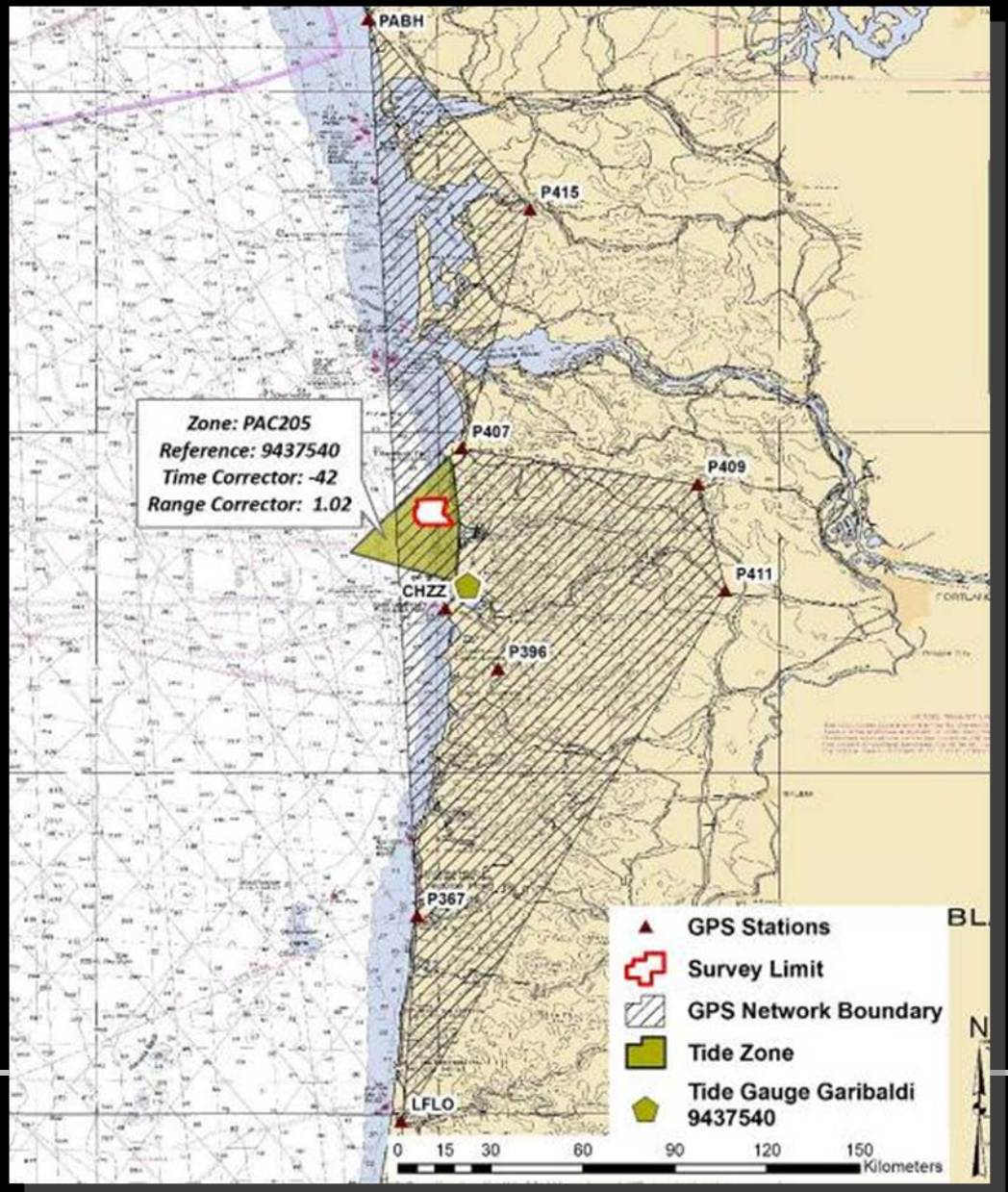

Oregon Coast Comparison of Zoned Tides and GPS Water Levels
DN282 - October 9, 2009
Astoria PAC211
Garibaldi PAC205
Smart Base PPK Water Levels
Zoned Tides Residual
MLLW (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0:00
2:24
4:48
7:12
9:36
12:00
14:24
16:48
19:12
21:36
0:00
Time

H12124 Test Area used for Comparison

- **Tides**
  - One Tide Gauge
  - One Tide Zone
  - Verified Tides Used
- **GPS**
  - 9 GPS Base Stations
  - Applanix SmartBASE
  - VDatum from NAD83 (GEOID 03) to MLLW applied in CARIS
- **Multibeam Data**
  - Collected over 5 days
  - 24 hour ops



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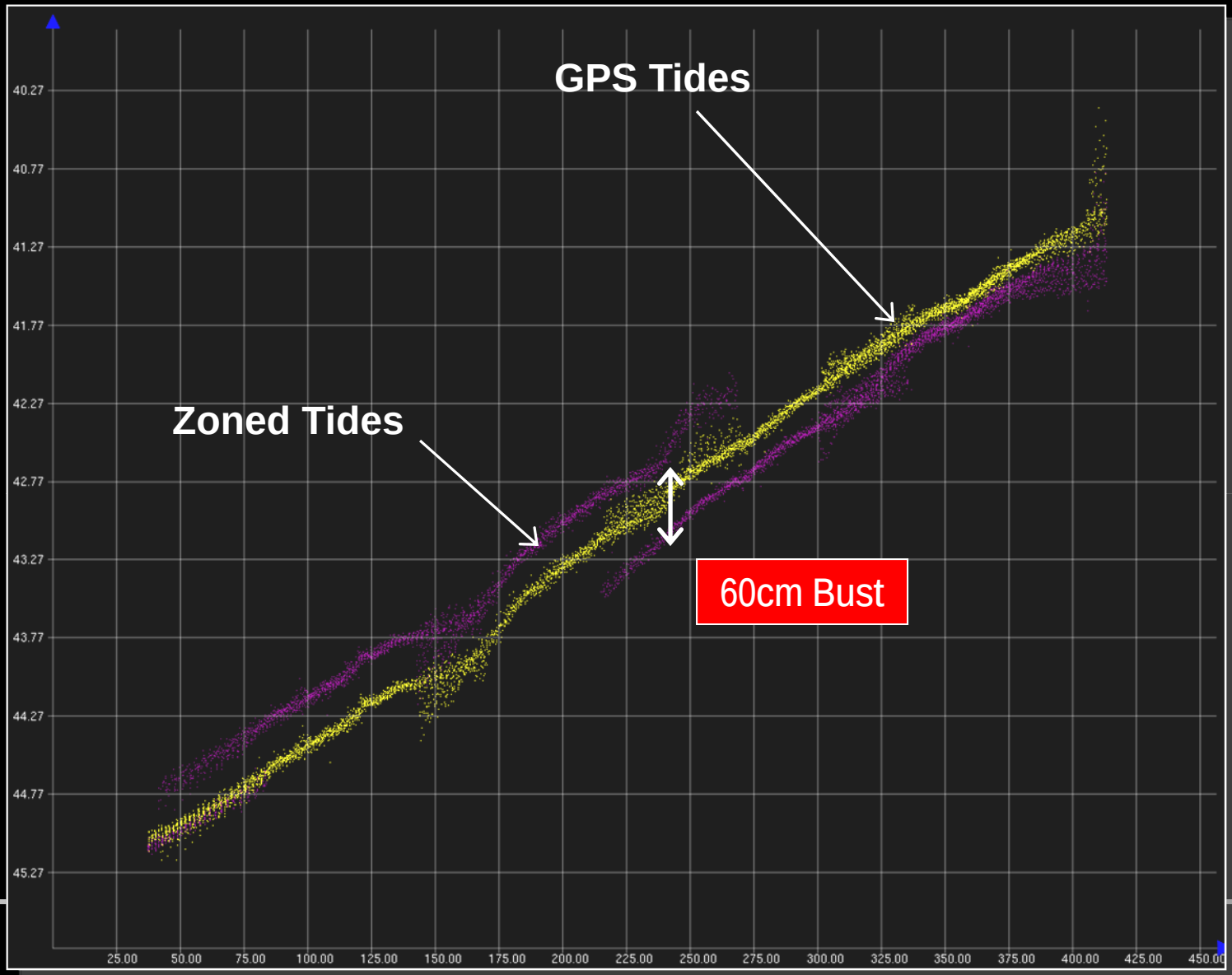
Comparison of Zoned Tides to Inertially-Aided GNSS



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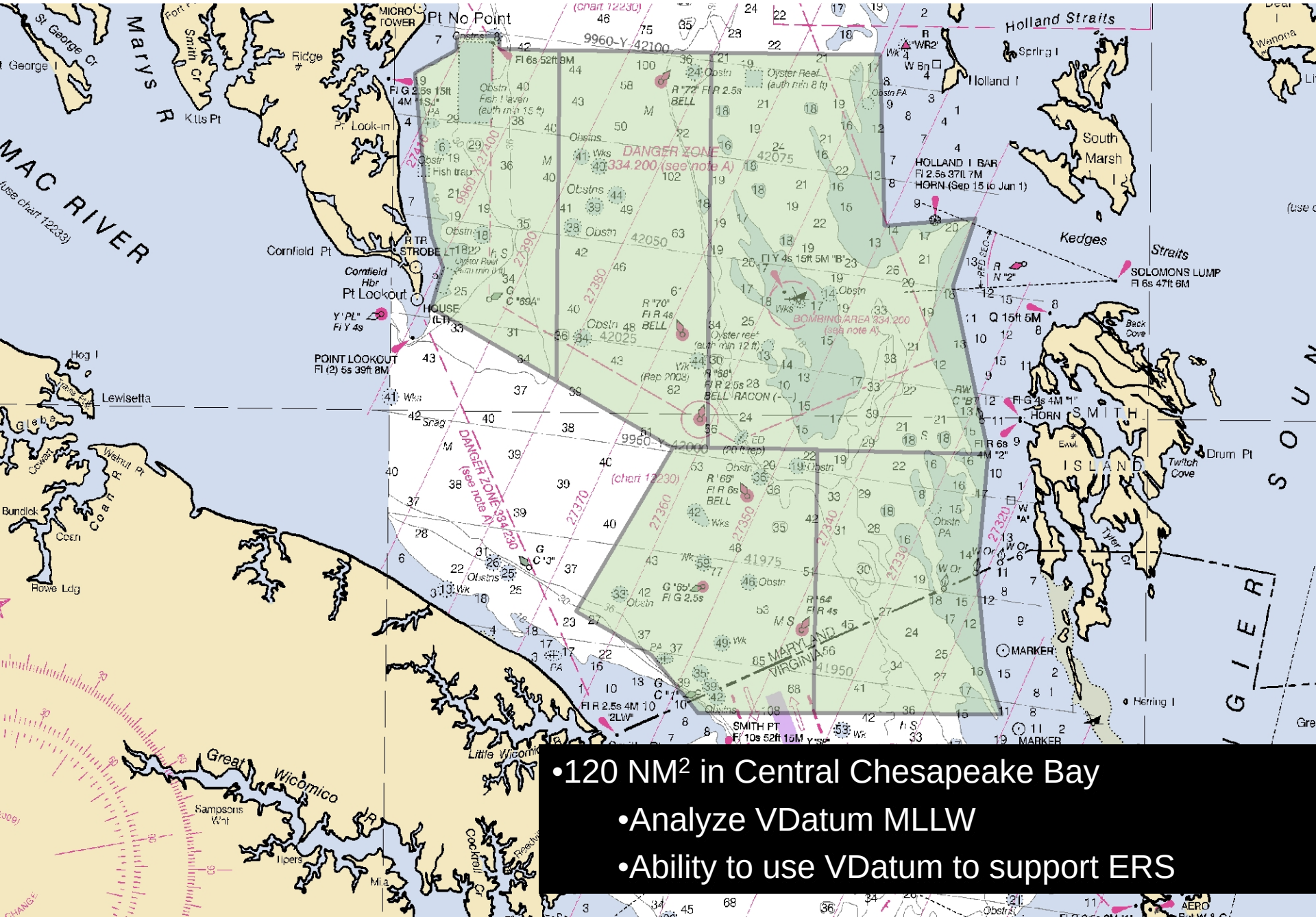
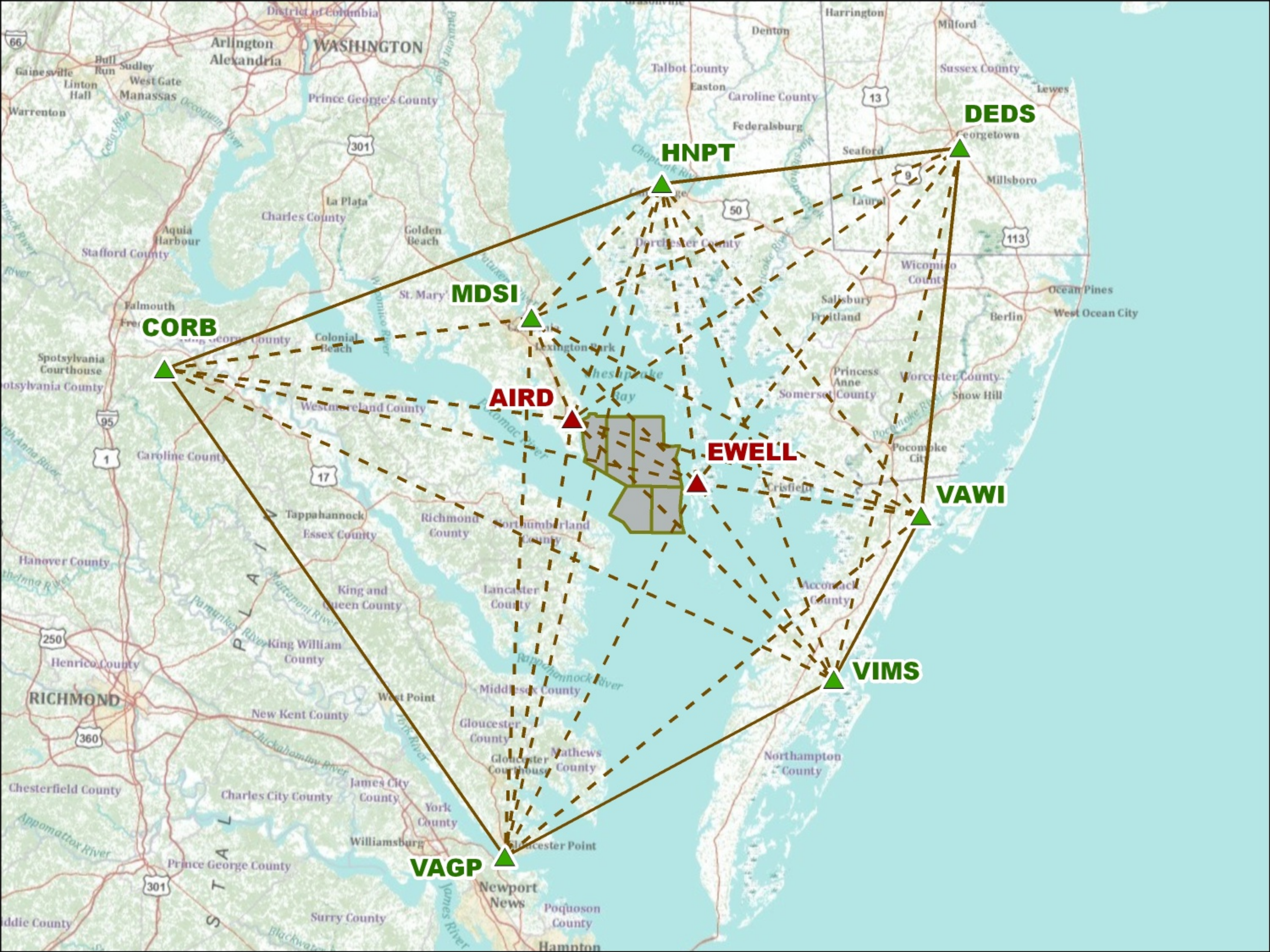
Chesapeake Bay 2010 Nautical Charting Survey



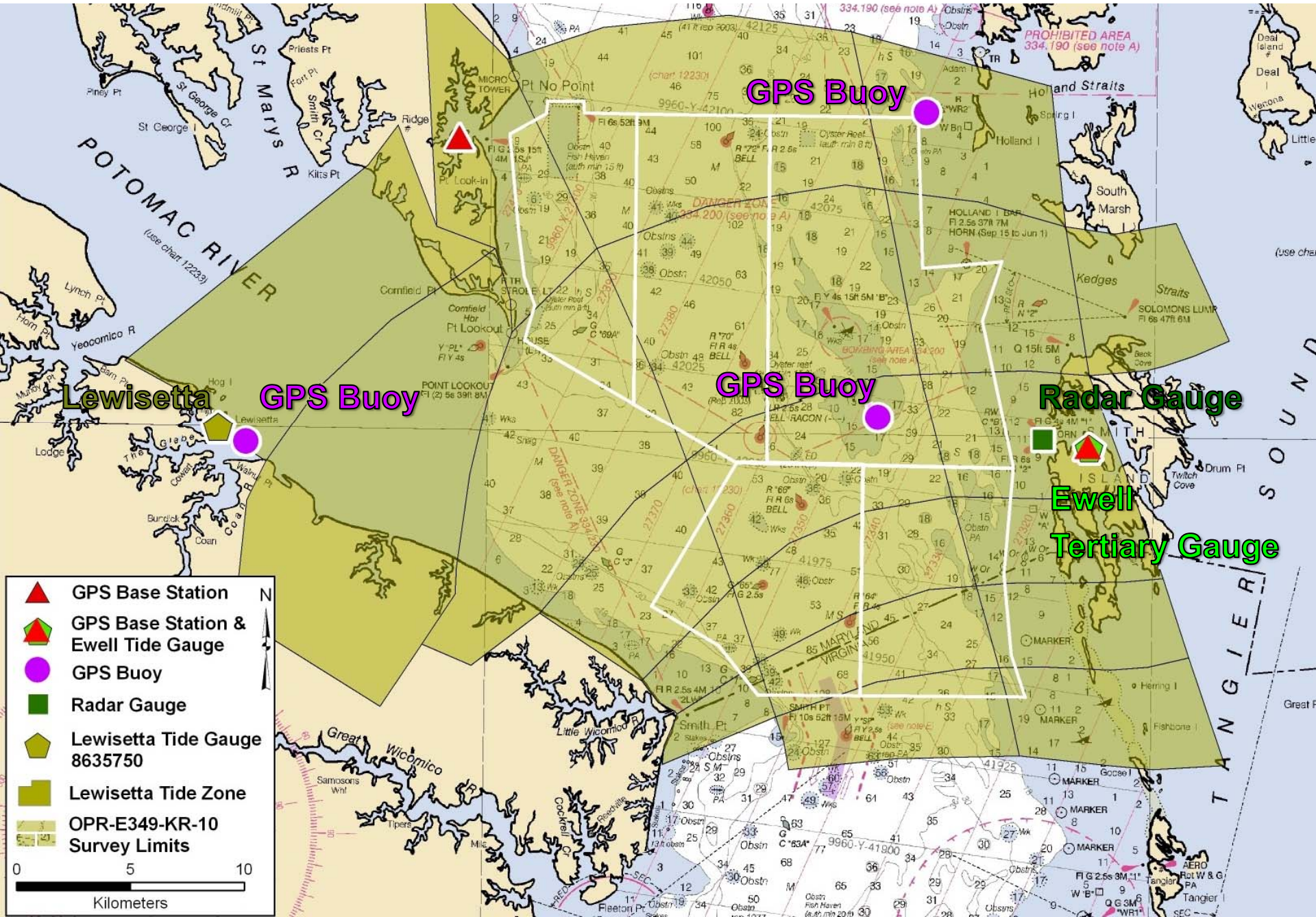
- 120 NM² in Central Chesapeake Bay
  - Analyze VDatum MLLW
  - Ability to use VDatum to support ERS

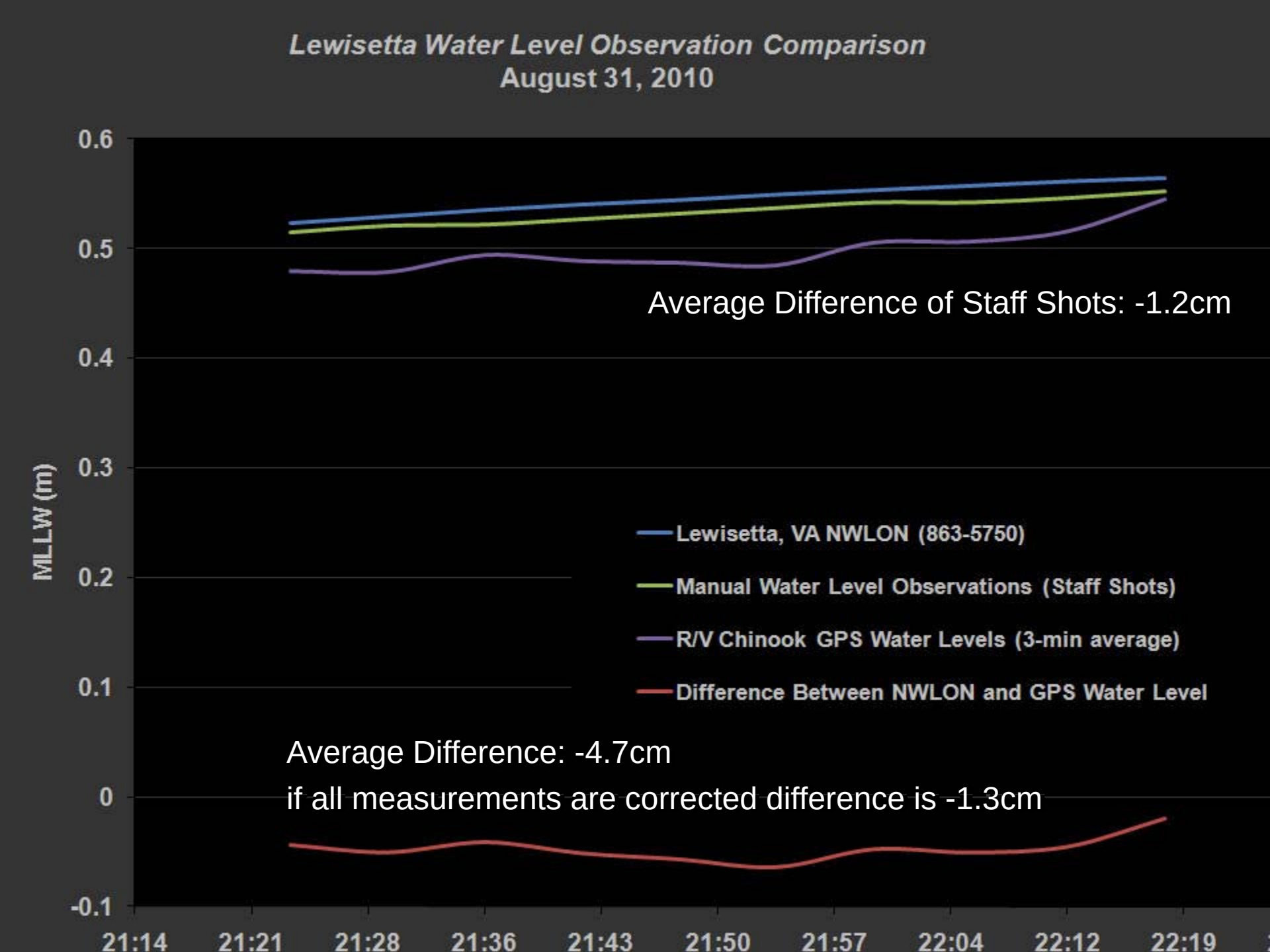
GNSS Network for Chesapeake Bay

- NGS CORS
- Installed 2 additional sites
  - Trimble Net-R5 GNSS dual frequency receivers
- Enabled post processing of GNSS data using Applanix POSPac SingleBase solution
- Backup network of cooperative CORS stations for Applanix POSPac SmartBase solution


DEDS
HNPT
MDSI
CORB
AIRD
EWELL
VAWI
VIMS
VAGP
WASHINGTON
District of Columbia
Arlington
Alexandria
Prince George's County
Charles County
Stafford County
St. Mary's
Lexington Park
Chesapeake Bay
Potomac River
Westmoreland County
Caroline County
Richmond County
Northumberland County
Lancaster County
Middlesex County
Gloucester County
Mathews County
King and Queen County
King William County
Hanover County
Henrico County
RICHMOND
New Kent County
Charles City County
James City County
York County
Williamsburg
Gloucester Point
Newport News
Hampton
Poquoson County
Chesterfield County
Prince George County
Surry County
Talbot County
Caroline County
Easton
Federalsburg
Seaford
Georgetown
Millsboro
Sussex County
Lewes
Milford
Harrington
Denton
Dorchester County
Wicomico County
Salisbury
Fruitland
Princess Anne
Somerset County
Worcester County
Snow Hill
Berlin
Ocean Pines
West Ocean City
Pocomoke City
Crisfield
Accomack County
Northampton County
Tappahannock
Essex County
Spotsylvania Courthouse
Spotsylvania County
Falmouth
Aquia Harbour
Colonial Beach
La Plata
Golden Beach
Manassas
Warrenton
Gainesville
Linton Hall
Bull Run
Sudley
West Gate
West Point
Gloucester Courthouse
Laurel

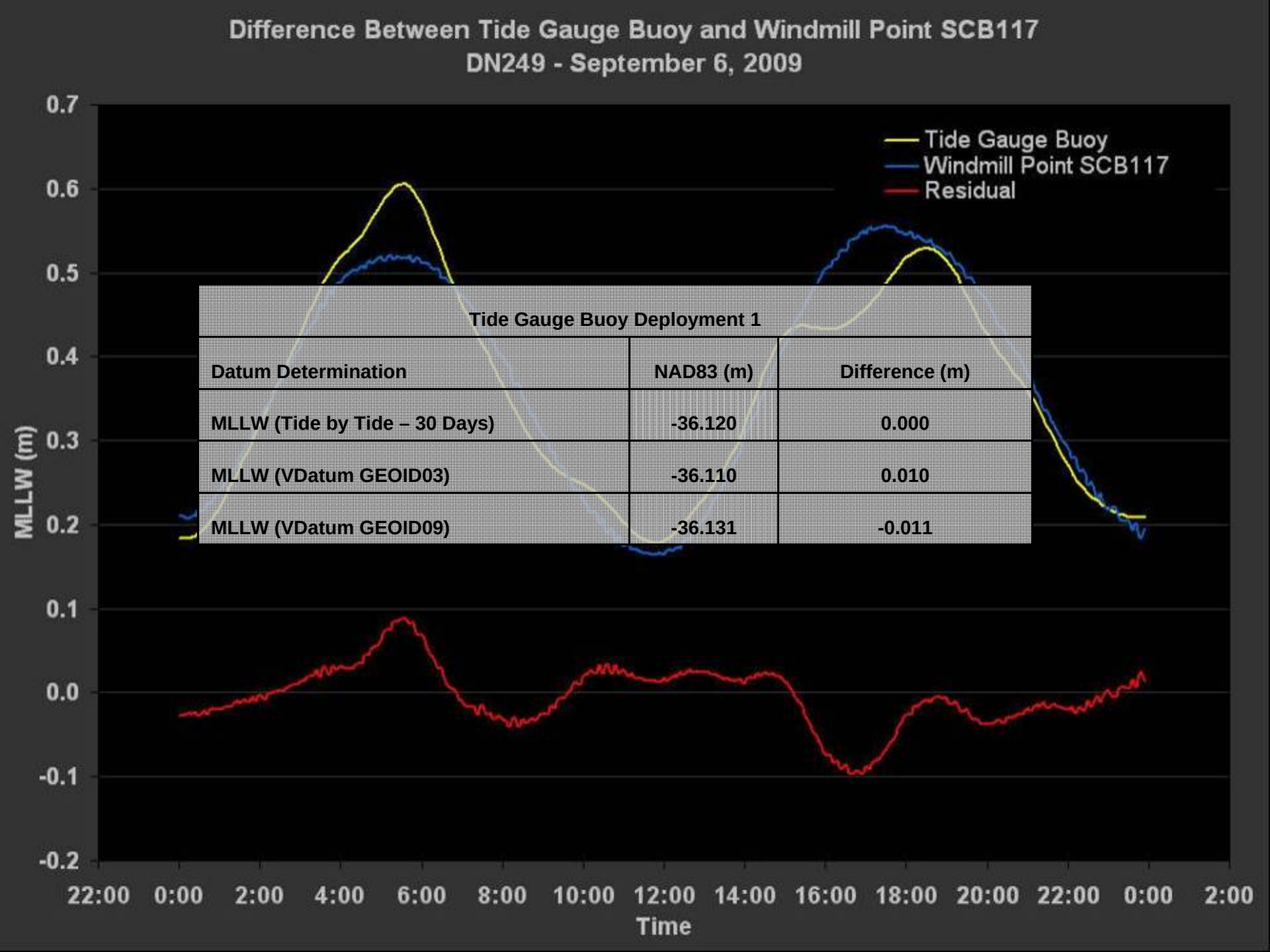
MLLW VDatum Evaluation



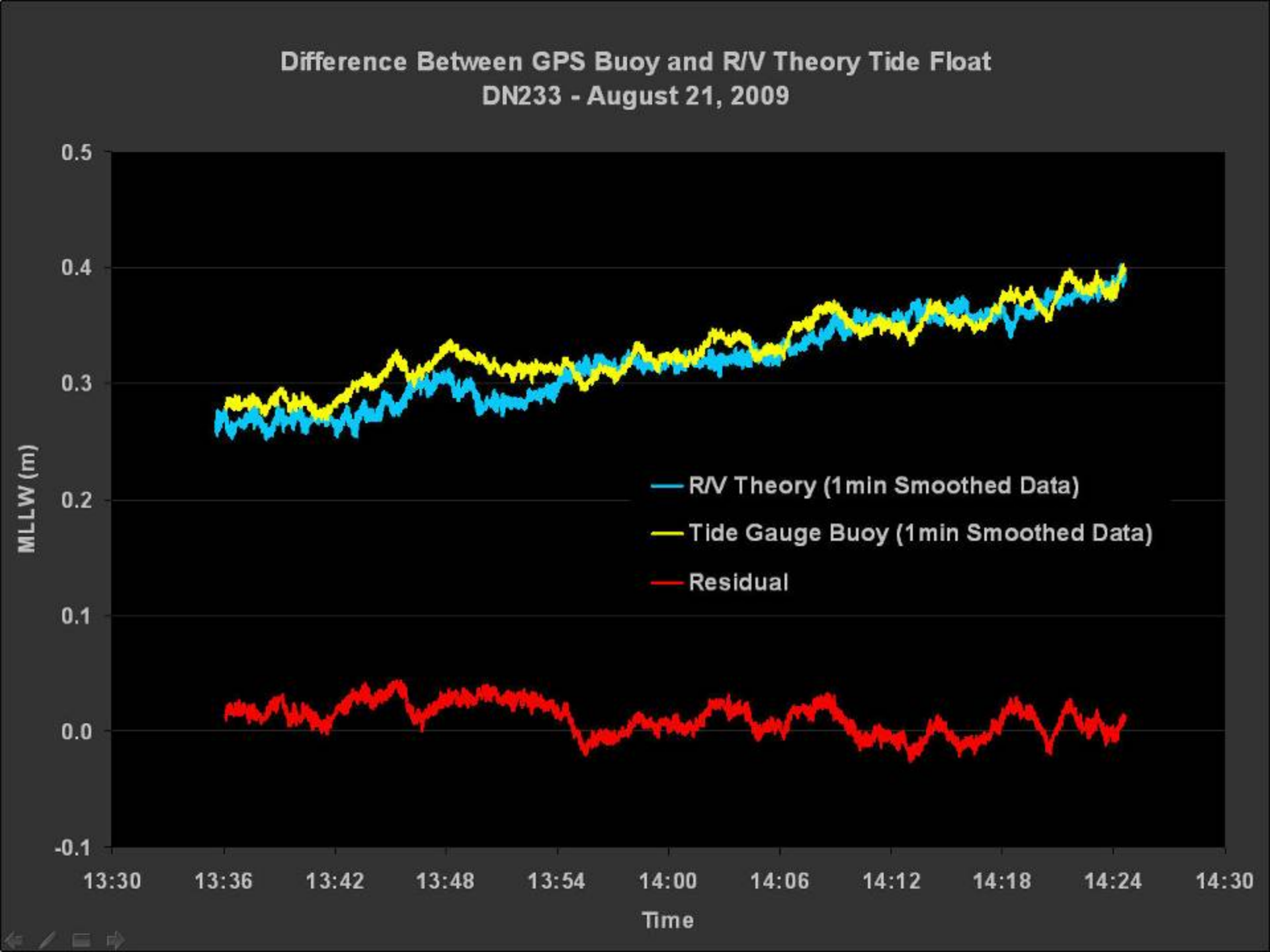

Lewisetta Water Level Observation Comparison
August 31, 2010
MLLW (m)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
21:14
21:21
21:28
21:36
21:43
21:50
21:57
22:04
22:12
22:19
Average Difference of Staff Shots: -1.2cm
Lewisetta, VA NWLON (863-5750)
Manual Water Level Observations (Staff Shots)
R/V Chinook GPS Water Levels (3-min average)
Difference Between NWLON and GPS Water Level
Average Difference: -4.7cm
if all measurements are corrected difference is -1.3cm

GPS Tide Buoy

- AXYS Technologies Hydro Level Mini GPS Buoy
- Deployed in 3 locations bracketing survey area
- Deployment 1 at Lewisetta NWLON as system check
- 30 day datums computed relative to NAD83



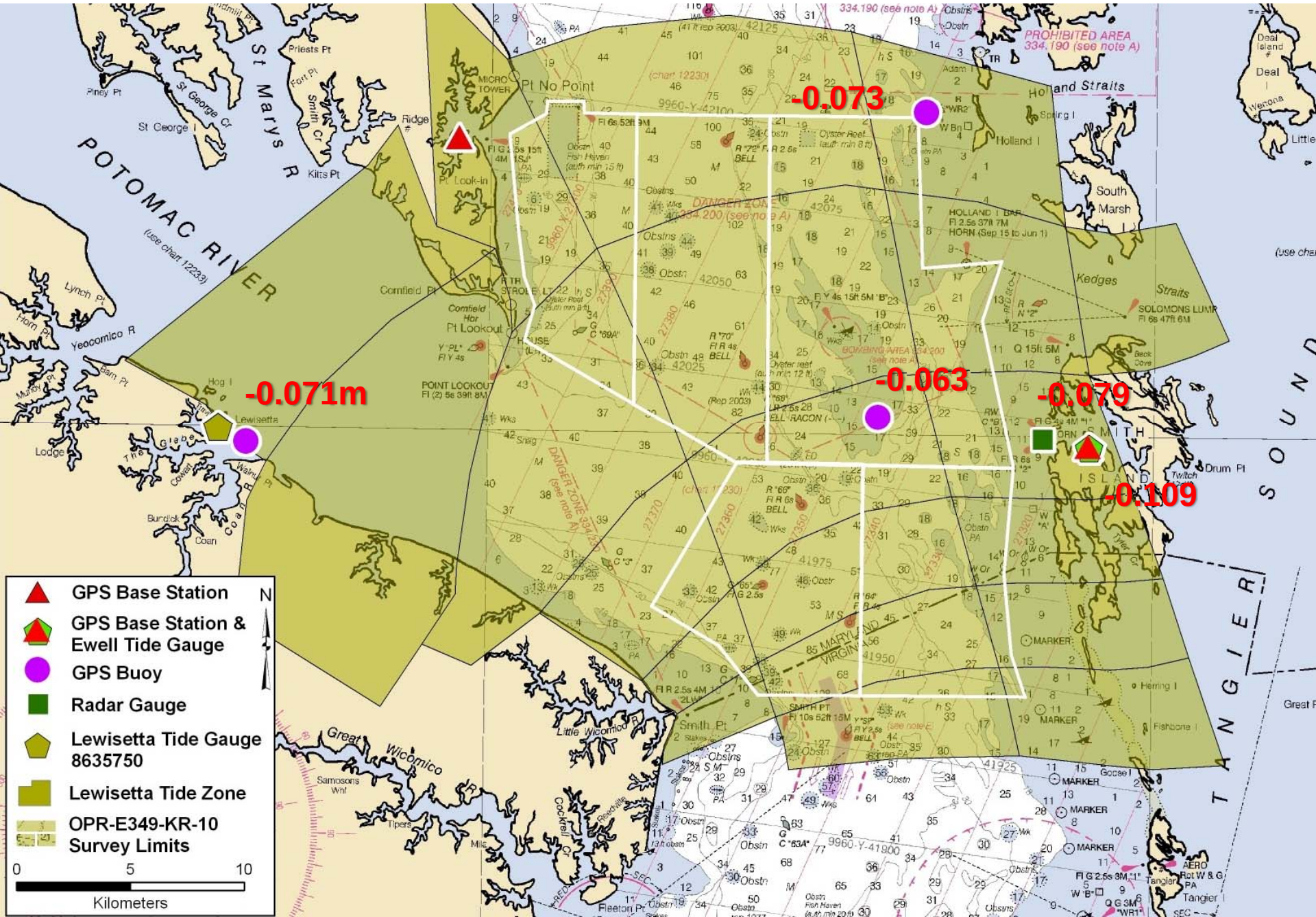
Tide Gauge Buoy Deployment 1		
Datum Determination	**NAD83 (m)**	**Difference (m)**
MLLW (Tide by Tide – 30 Days)	**-36.120**	**0.000**
MLLW (VDatum GEOID03)	**-36.110**	**0.010**
MLLW (VDatum GEOID09)	**-36.131**	**-0.011**


Difference Between GPS Buoy and R/V Theory Tide Float
DN233 - August 21, 2009
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
MLLW (m)
R/V Theory (1min Smoothed Data)
Tide Gauge Buoy (1min Smoothed Data)
Residual
13:30
13:36
13:42
13:48
13:54
14:00
14:06
14:12
14:18
14:24
14:30
Time

Radar Gauge

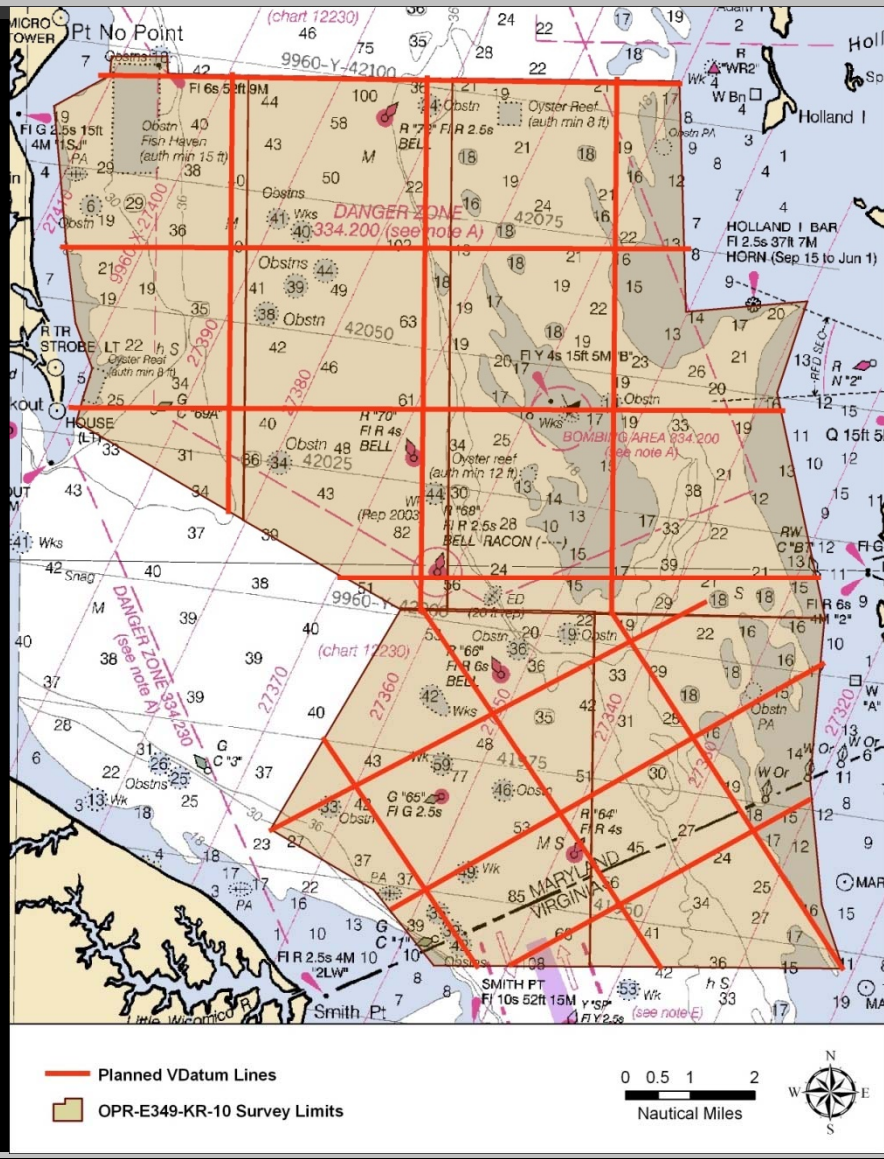
- Installed on USCG Light west of Smith Island
- DAA Waterlog H3611
- Deployed for 90 day datum
- Ellipsoid height determined by GNSS

VDatum Differences



VDatum Test Lines

- Predetermined test lines
- Followed the slope of the geoid
- Followed the largest tide zoning range and phase correctors



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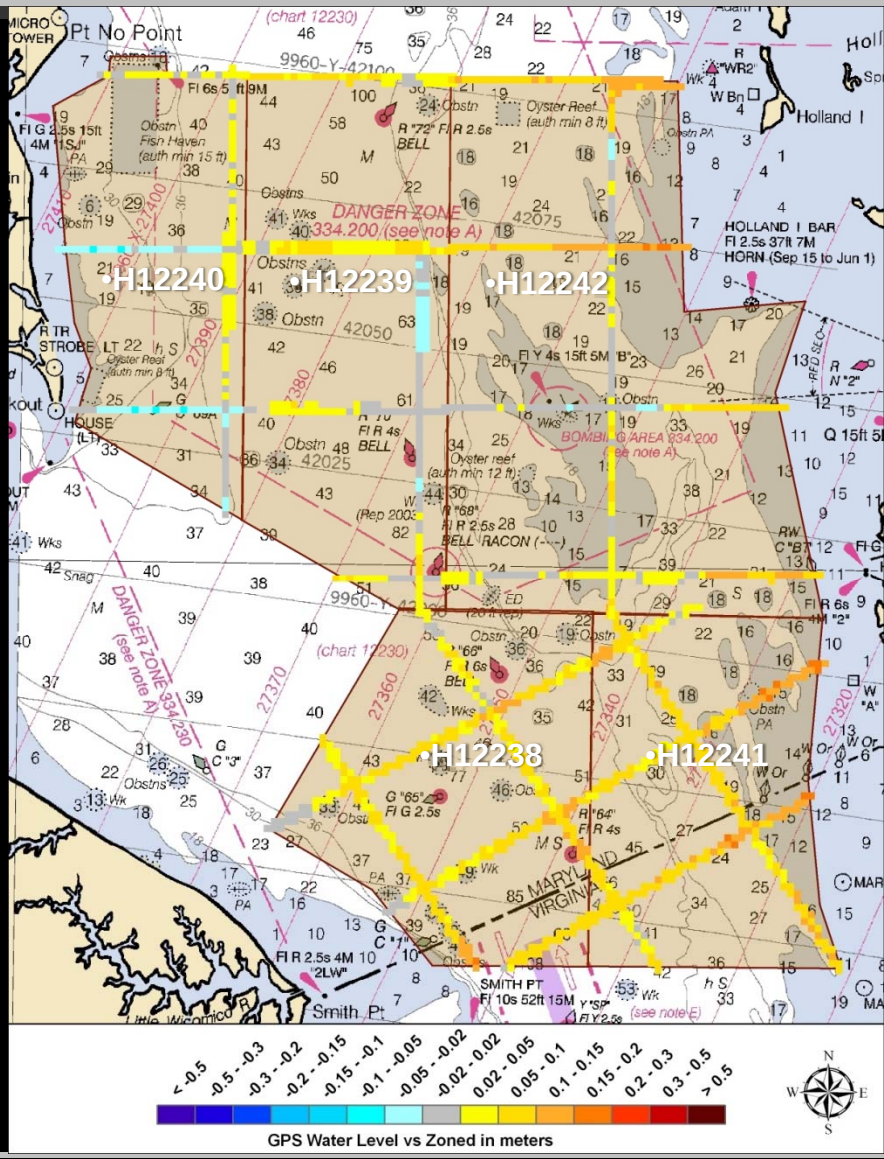
Analysis of VDatum Test Lines

Survey	Minimum (m)	Maximum (m)	Mean (m)	Median (m)	Standard Deviation (m)
H12238	-0.030	0.180	0.062	0.060	0.032
H12239	-0.100	0.100	0.025	0.030	0.030
H12240	-0.110	0.100	0.002	0.010	0.033
H12241	-0.010	0.180	0.076	0.070	0.031
H12242	-0.090	0.180	0.050	0.040	0.047

- *zoned tide greater than GPS water level*
- *zoned tide less than the GPS water level*



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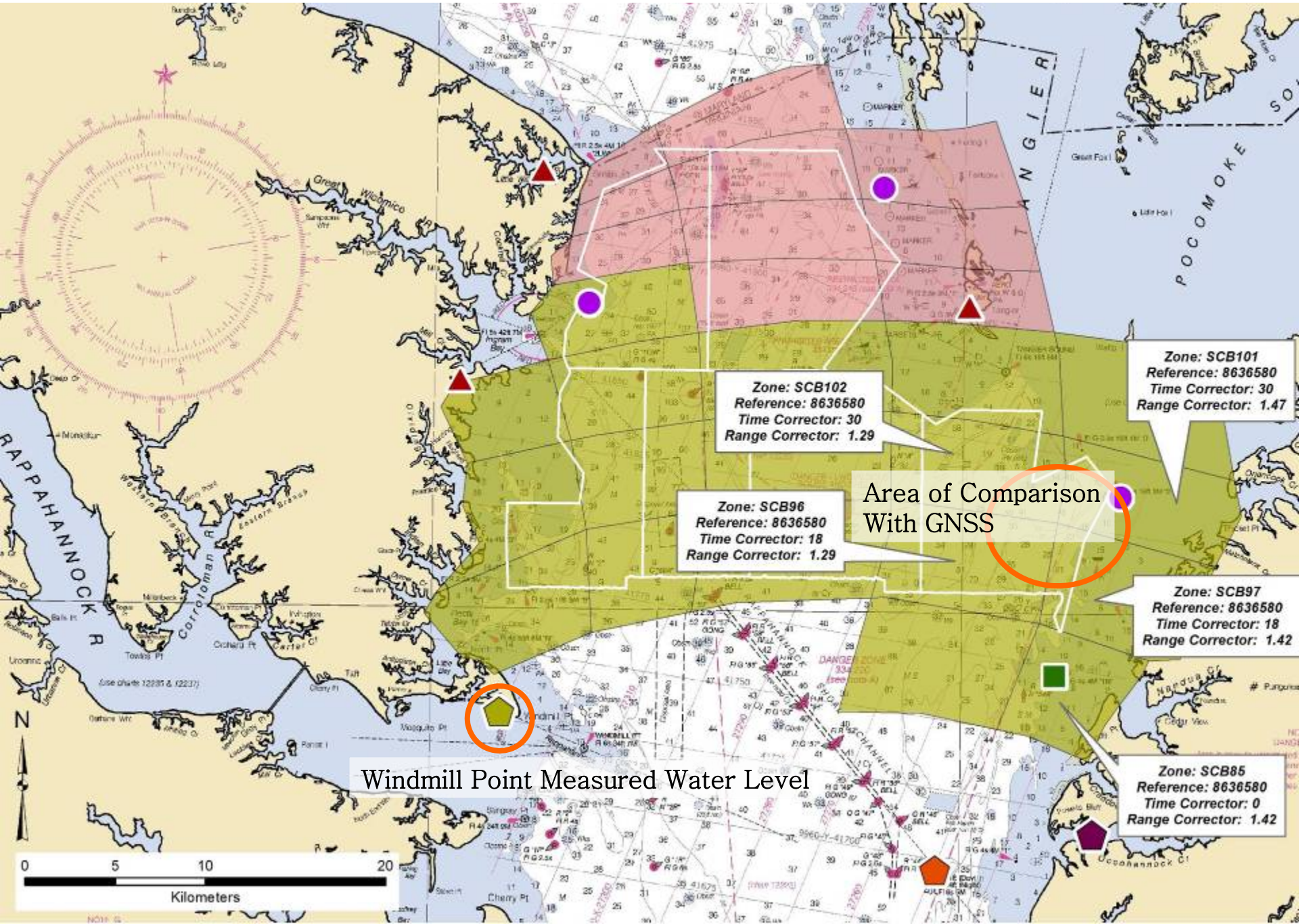
Zoned Tides Vs. Vessel Inertially-Aided GNSS Measured Tides



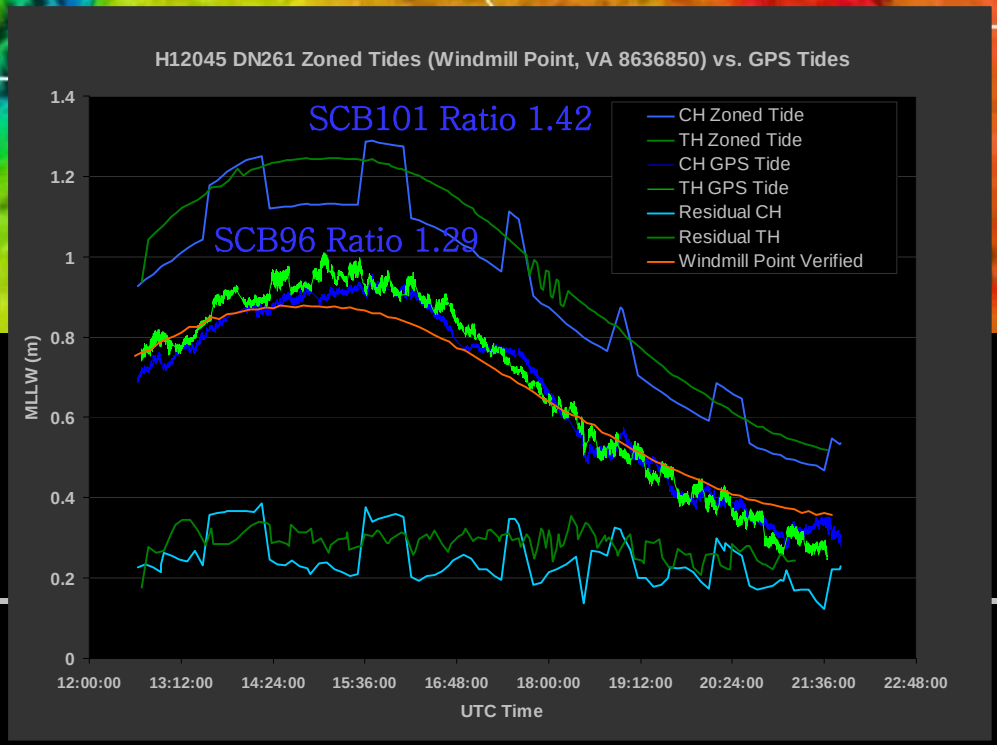
SCB102 Ratio 1.29

SCB101 Ratio 1.47

Post-Processed SBET file

SCB97 Ratio 1.42

SCB96 Ratio 1.29



Zoned tides jump 18 cm between SCB 96 and SCB 101 at 1 meter tide level.

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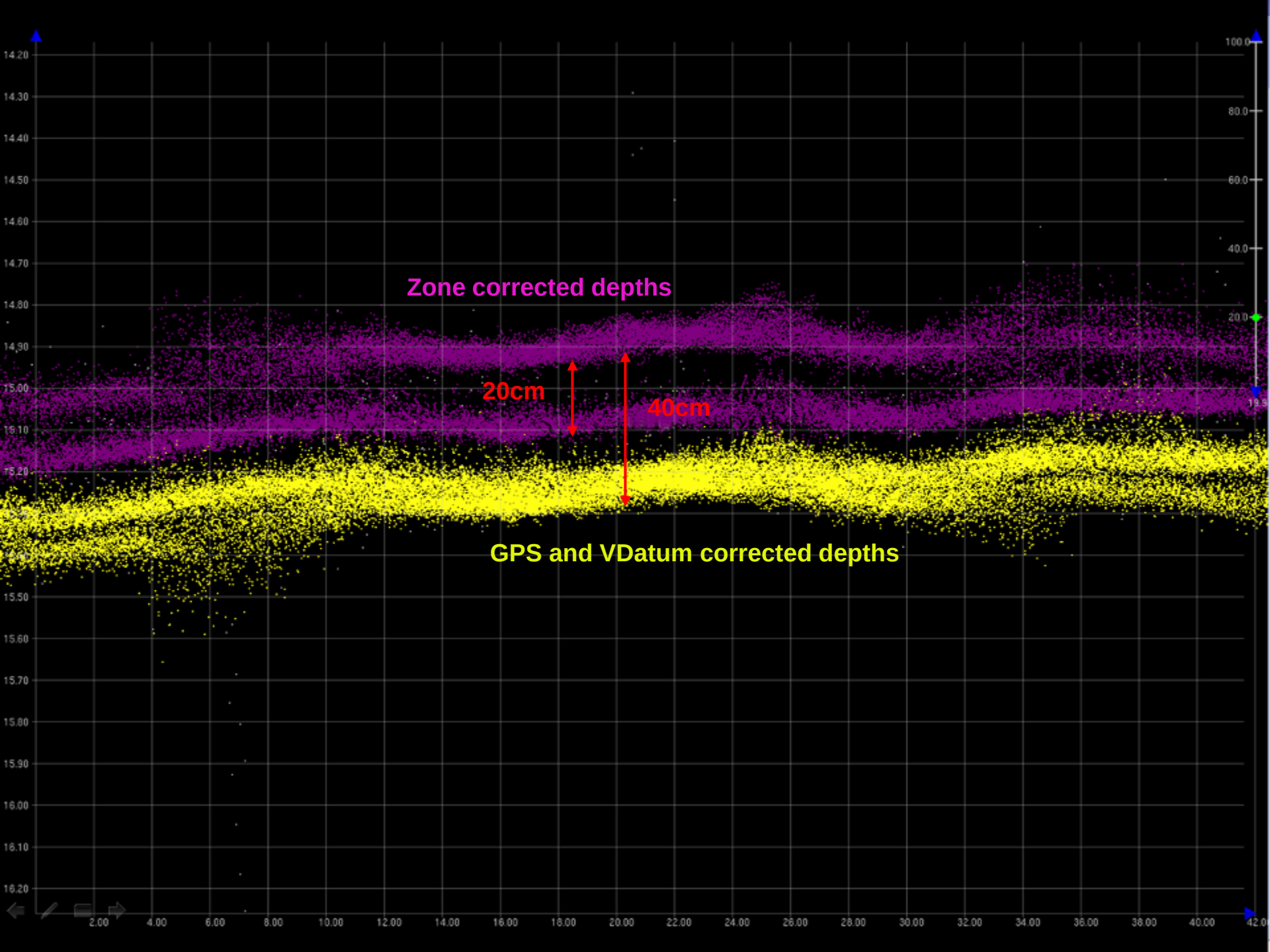
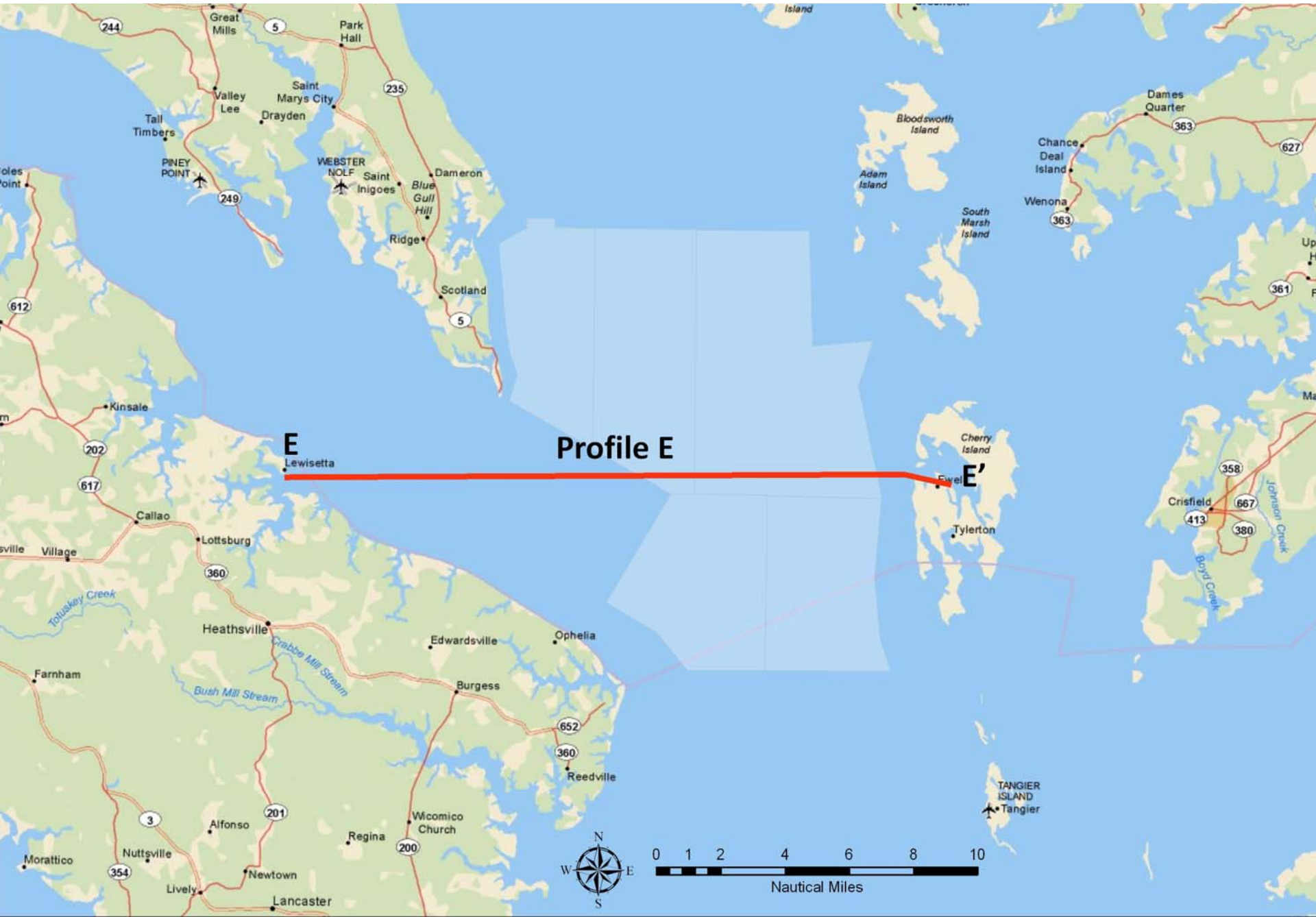
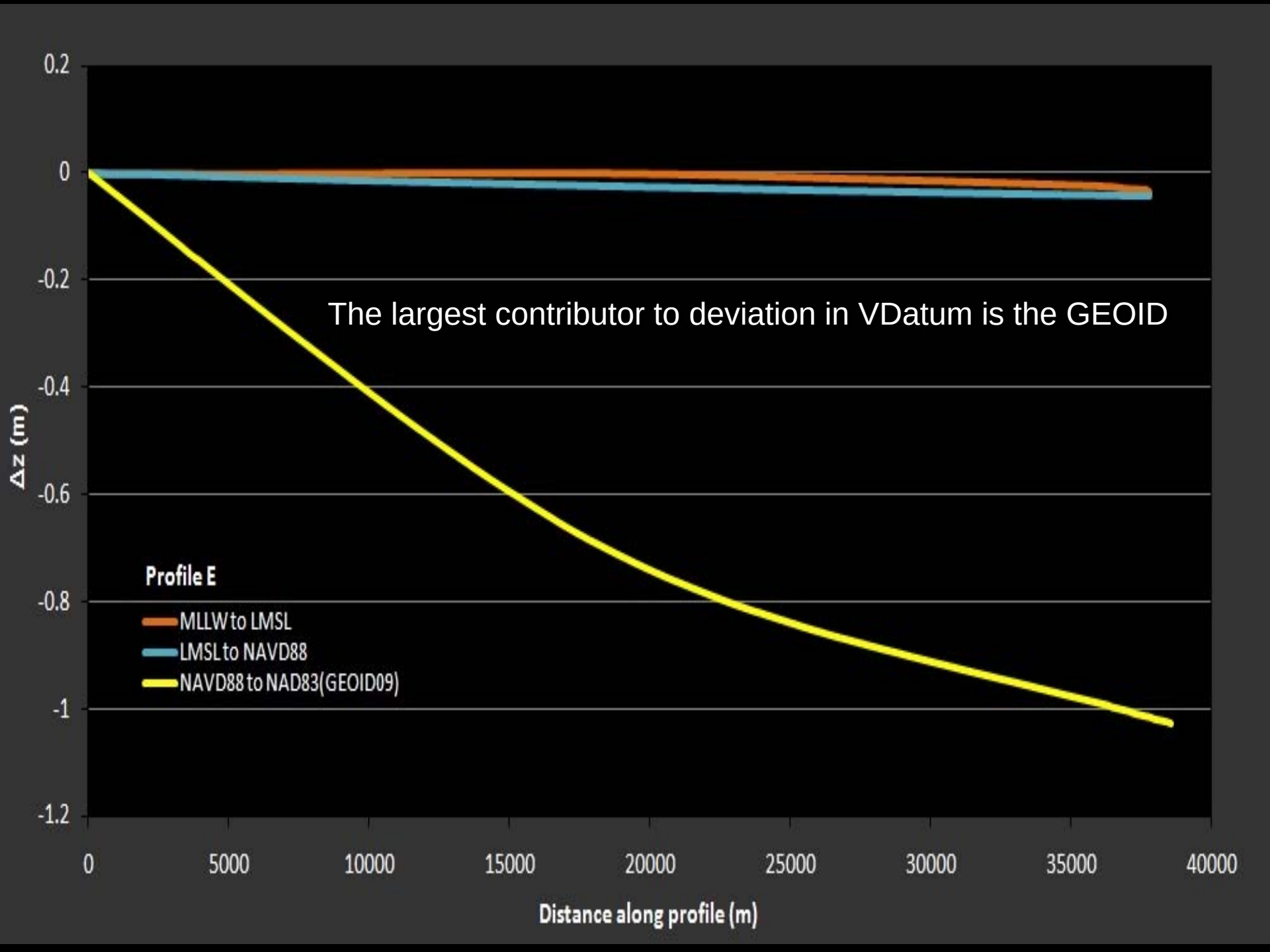
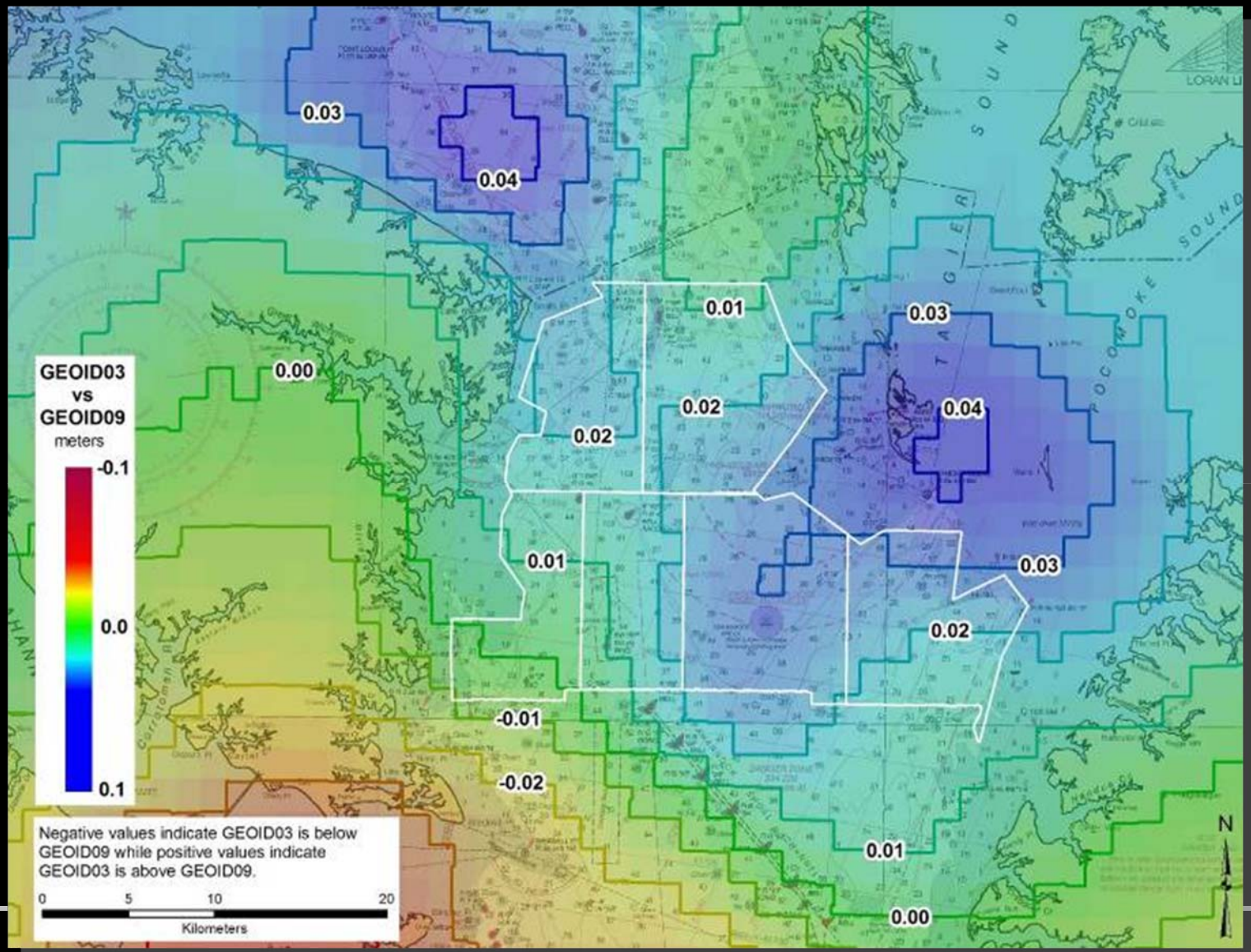

Zone corrected depths
20cm
40cm
GPS and VDatum corrected depths

Profile of VDatum Components




0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Δz (m)
The largest contributor to deviation in VDatum is the GEOID
Profile E
MLLW to LMSL
LMSL to NAVD88
NAVD88 to NAD83(GEOID09)
0
5000
10000
15000
20000
25000
30000
35000
40000
Distance along profile (m)

Impact of GEOID03 versus GEOID09 over Survey Area



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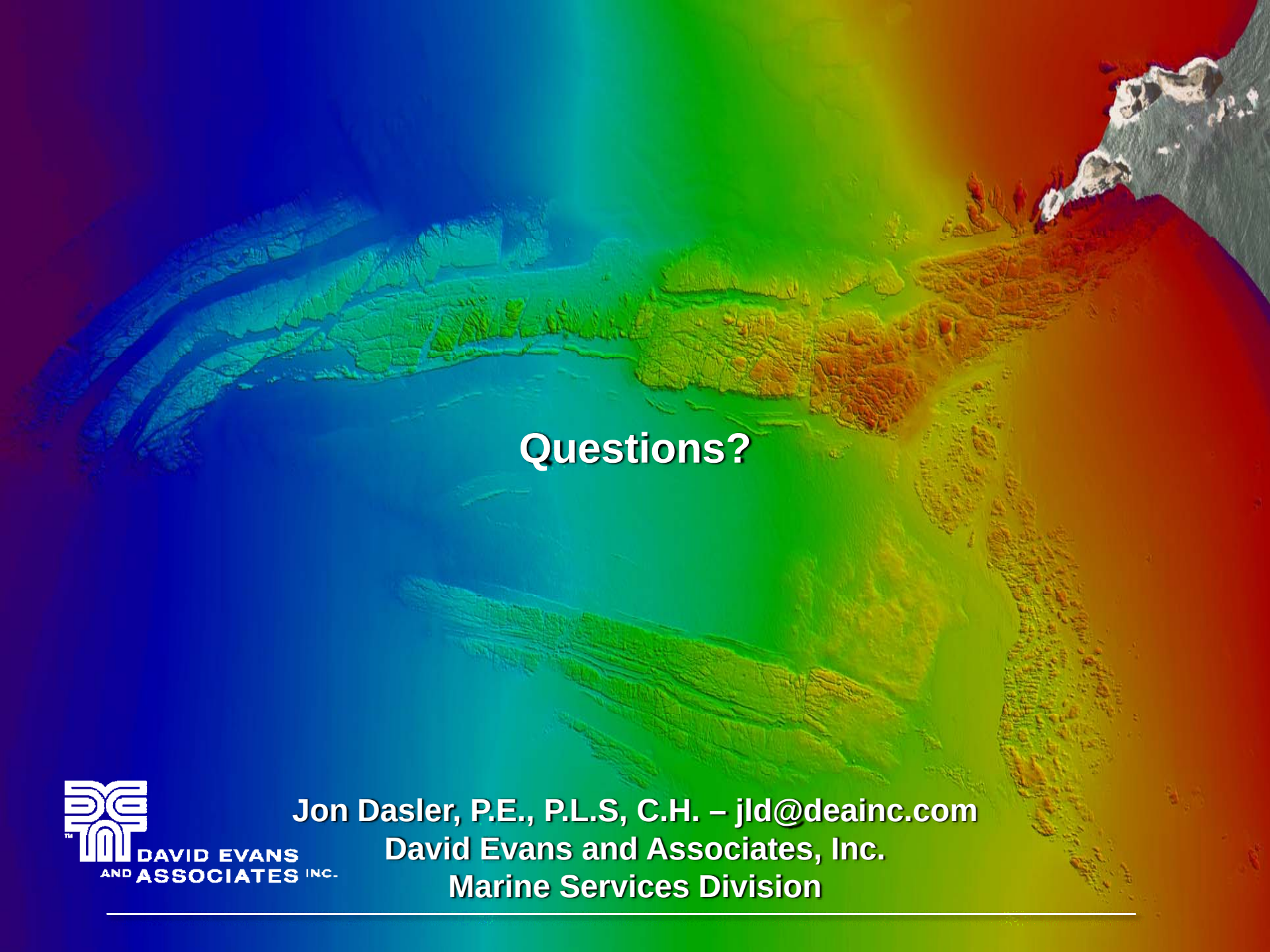
Comparison of Water Level Uncertainty Values

Table 1 Chesapeake Bay Project Vertical Uncertainty

Method	Heave	Tide Measured	Tide Zoned	Delta Draft	Loading	Draft	Total Component
Traditional Ranges [i]	*0.05*	*0.01-0.05*	*0.01-0.40*	*0.01-0.03*	*0.01-0.30*	*0.01-0.20*	*0.05-0.544*
Zoned Tides	0.050	0.000[ii]	0.080	0.040	0.020	0.010	0.105*
GPS Water Levels (w/ heave)	0.050	0.035[iii]	0.084[iv]	0.000	0.000	0.000	0.103
GPS Water Levels (w/o heave)	0.000	0.035[iii]	0.084[iv]	0.000	0.000	0.000	0.091

[i] NOAA Field Procedures Manual 2008, Chapter 4 Appendices
[ii] Total Tide Uncertainty Value for Windmill Pont to Tangier Island included in the Tide Zoned Field
[iii] GPS Height Measurement Uncertainty
[iv] Separation Model Uncertainty

** Zoned Tides uncertainty is low and should be closer to 20 to 40 cm in some areas*



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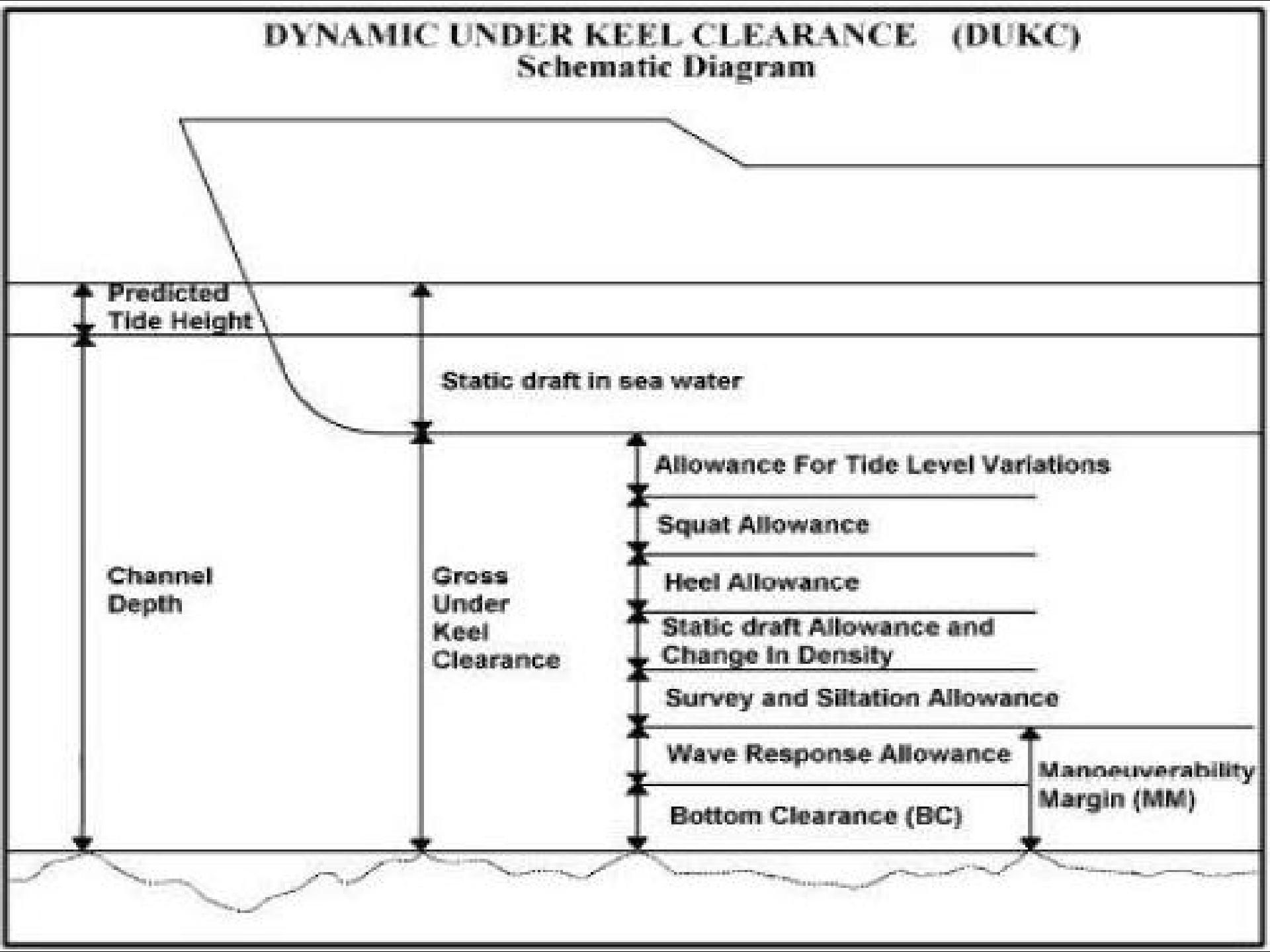
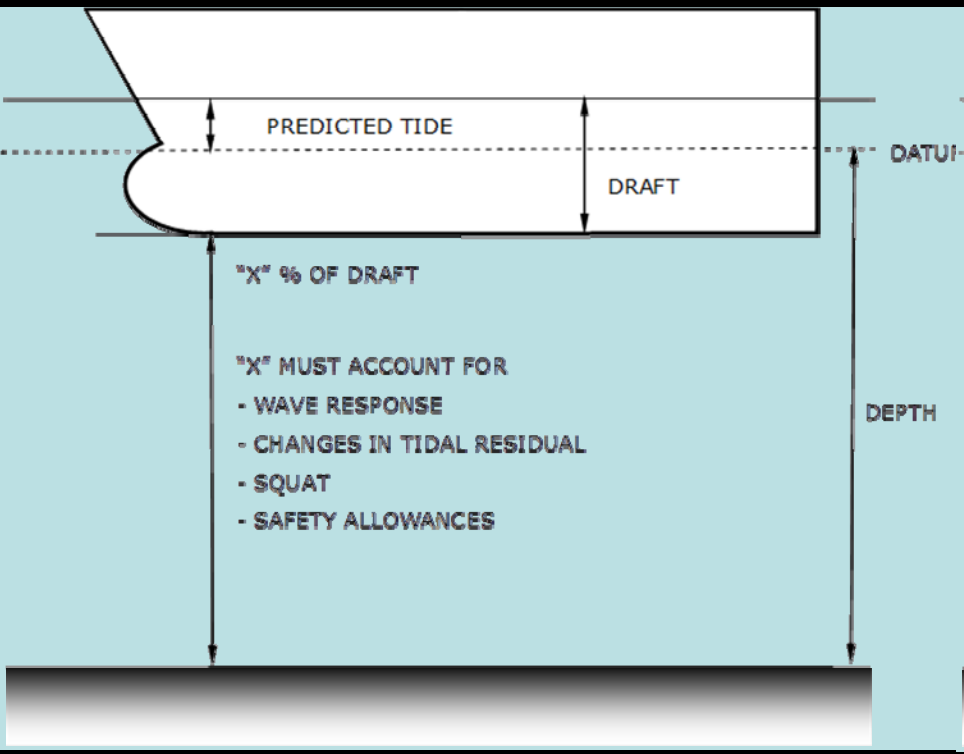
David Evans and Associates, Inc.
Marine Services Division

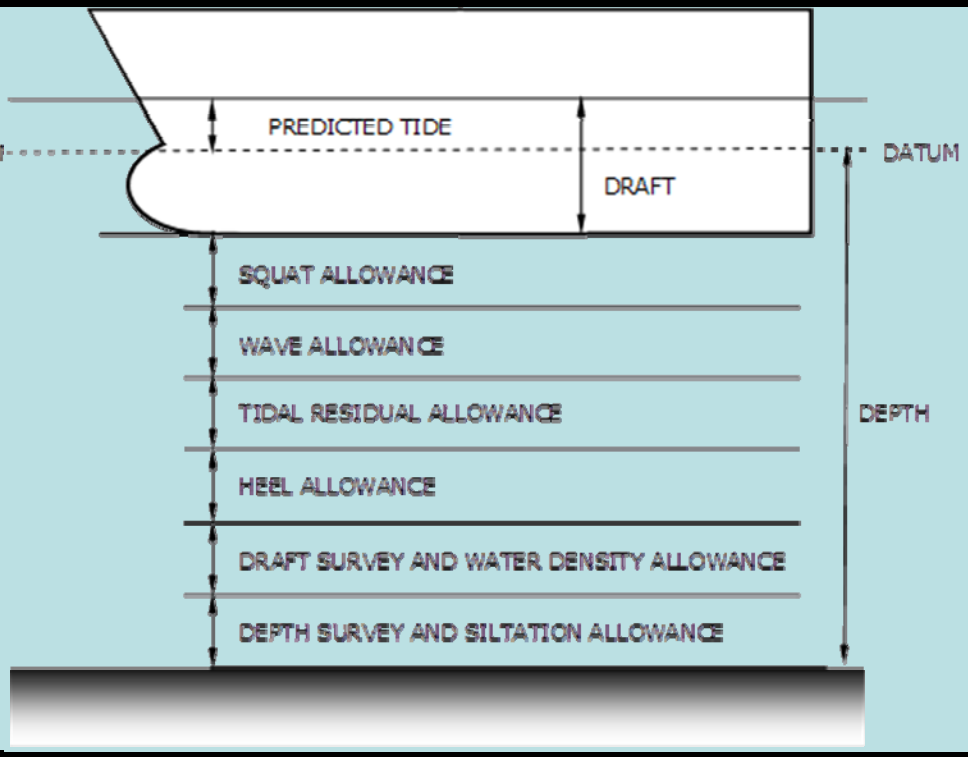
DYNAMIC UNDER KEEL CLEARANCE (DUKC)
Schematic Diagram



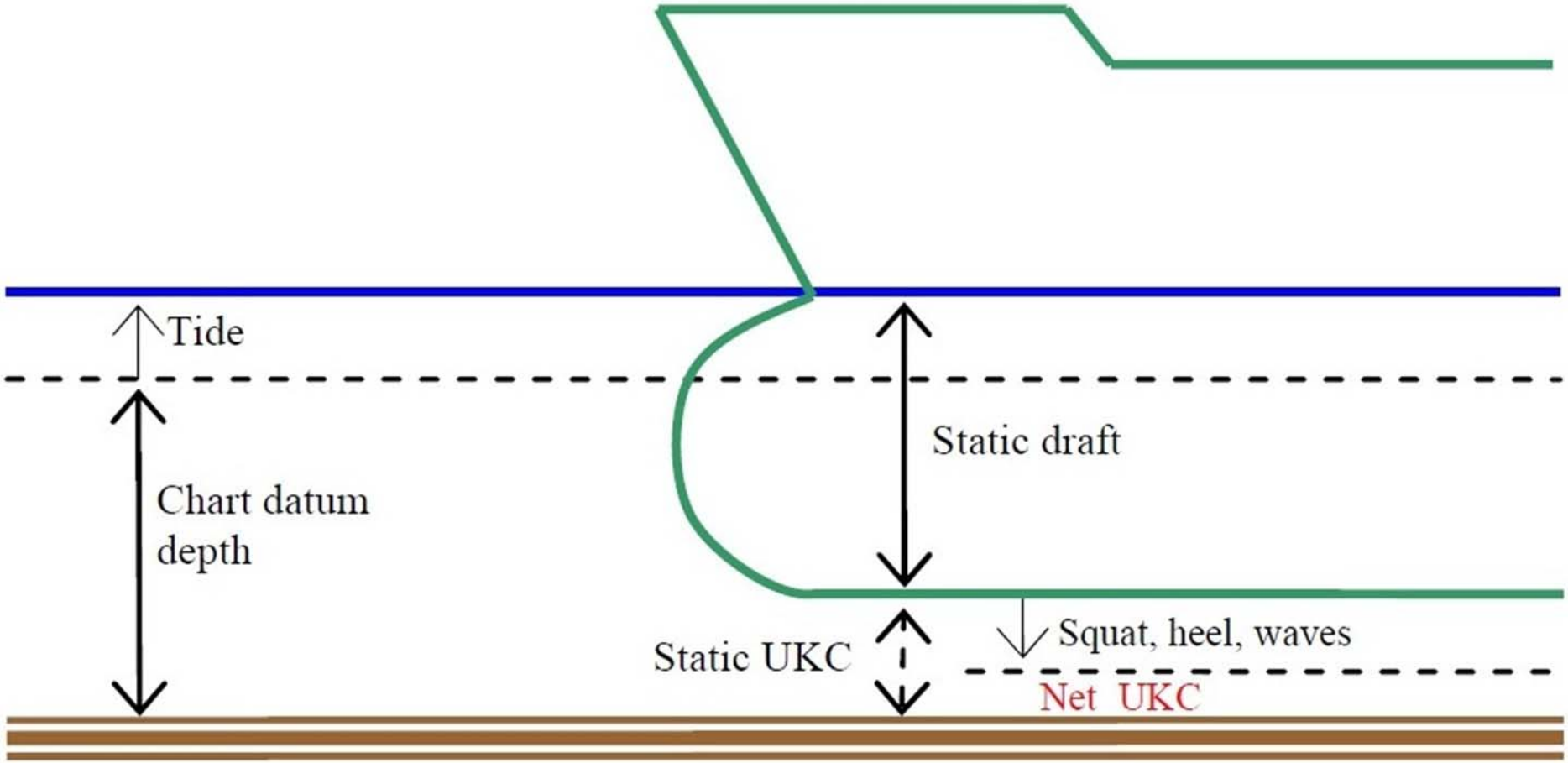
Static UKC



Dynamic UKC

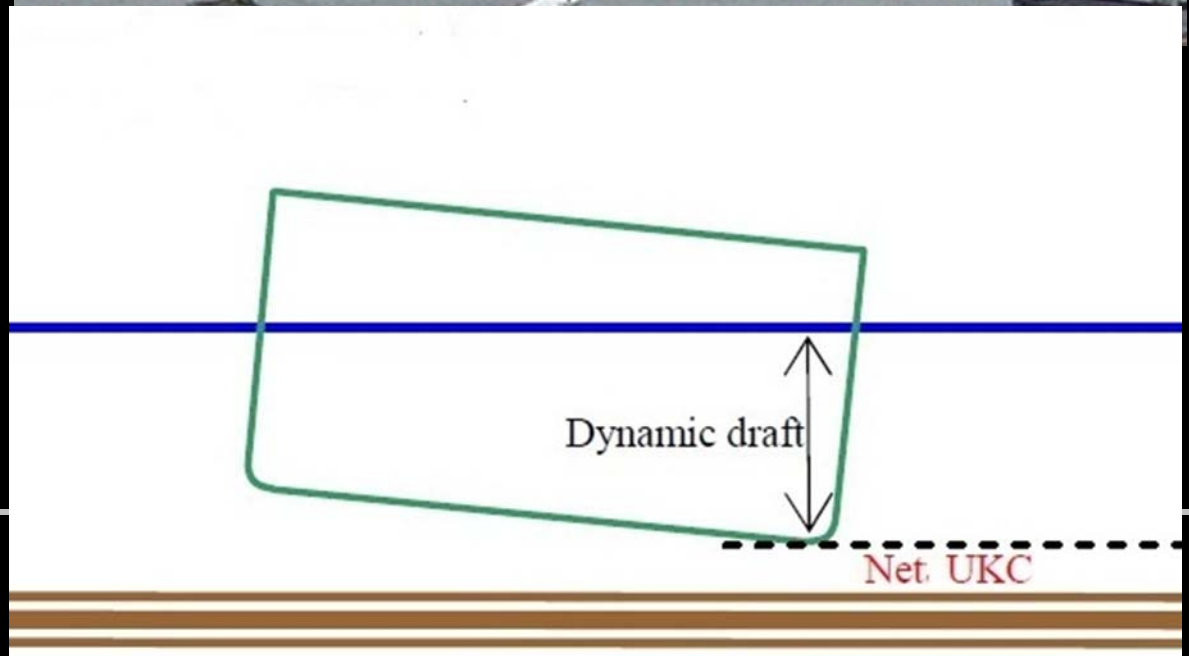


Maneuverability Margin, Safety Margin, Bottom Clearance or Net UKC



Roll / Heel

1 foot per degree (100ft beam)



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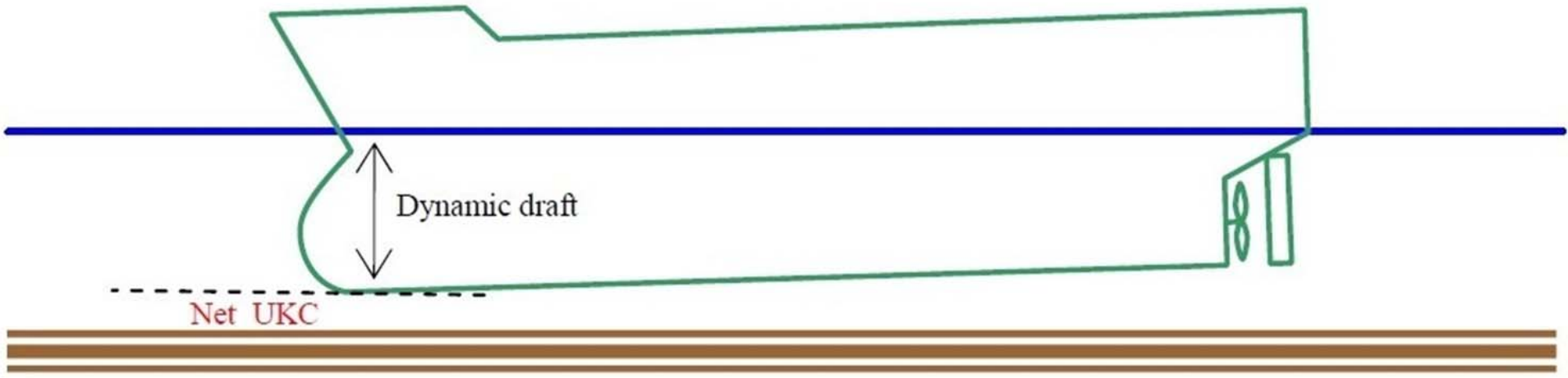
Pitch / Squat



Striking bottom in a harbor entrance

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- Three onboard GNSS units
  - Port & Stbd bridge wings
  - Bow
- Shore-side GNSS units
- Inertially-aided GNSS equipped survey boat

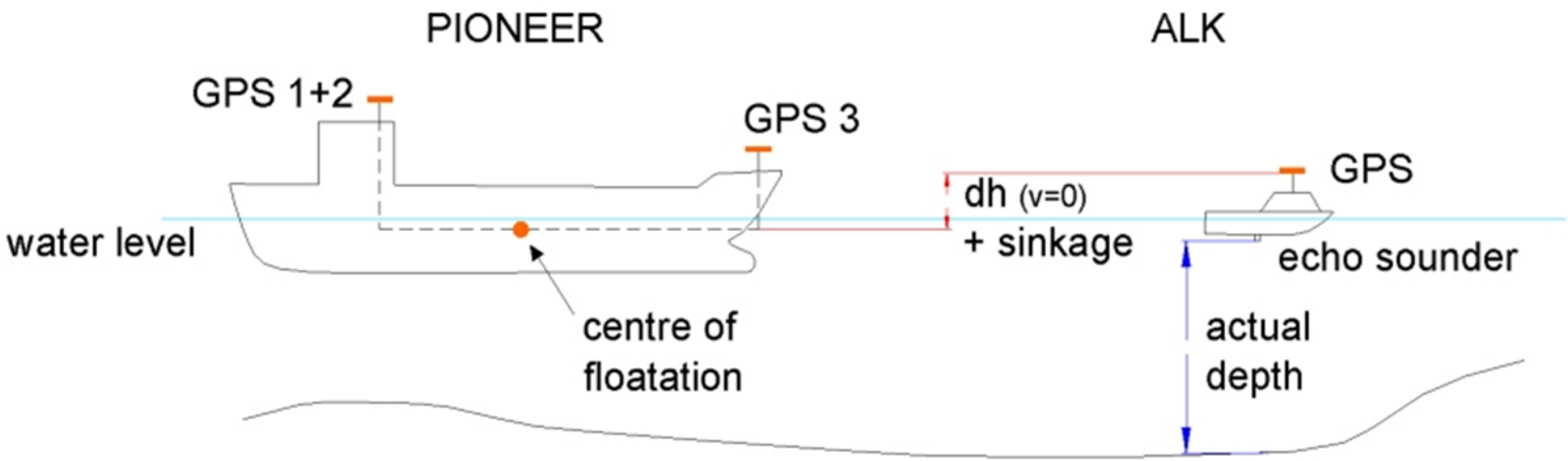
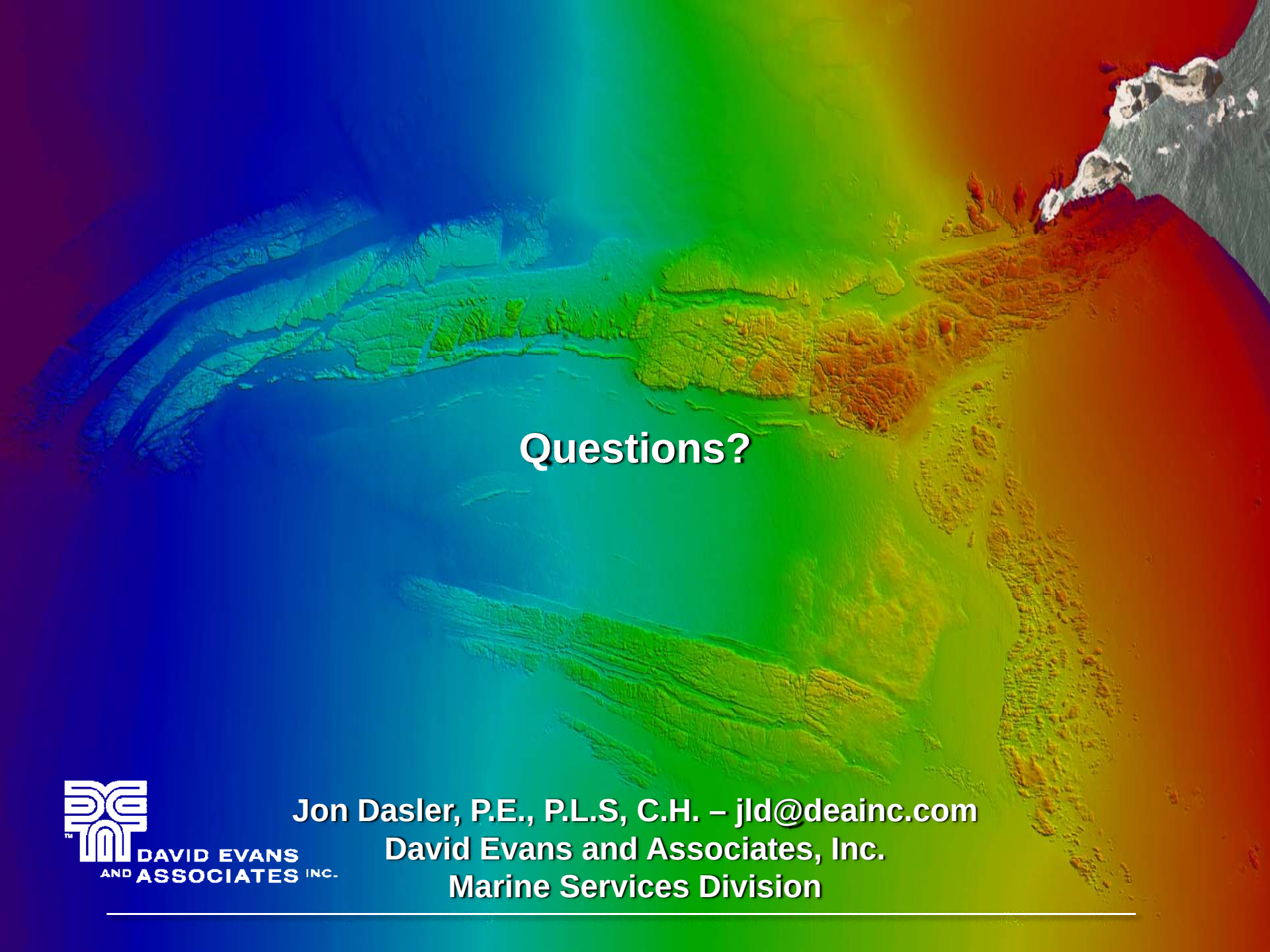


Fig. 1: Simplified geometry: Alk escorting Pioneer



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