Assured PNT
Strengths and Synergies

Contributions of GNSS manufacturers to the U.S. economy

Economic Benefits	Total
Direct Economic Impacts	
Total Revenues	$16.0 billion
Total Value Added	$9.1 billion
Total Payrolls	$3.5 billion
Number of Employees	42,126
Payroll per Employee	$81,969
Direct and Indirect Economic Impacts	
Output	$32.0 billion

Will be updated at this meeting

So what is the Problem?

- **High-level USG Official:**

  "GPS is much too vulnerable, we must ***replace*** it with new ***Inertials*** [Instruments] and Chip Scale Atomic Clocks [CSAC]"

- Indeed, GPS has a very weak signal, and also depends on Line of Sight to at least 4 satellites,

  But…

- **IMHO – *Better Statement* – the "PTA" solution:**

  "We must ***P***rotect, ***T***oughen, and ***A***ugment GPS to ensure that it meets User's PNT needs"

A matter of Record - Strengths and Synergies

- GPS/GNSS
- Inertial Systems and Components
- eLoran

Summarizing GPS Characteristics

Jam Resistance - the *"Nibbles"*

Improving Jamming Resistance Performance

Digital Technology is making beam steering and vector receivers much more affordable

Believe This is a trend that will continue

Ine (MEM		
Wider Spreading GNSS Signal (e.g. L1C)	5 dB	32%
Digital Beam Forming Antenna	20-30 dB	1.0% - 0.1%
Aircraft Shading (commercial Aircraft)	5-10 dB	32% - 10%
"Spilker" Vector Receiver (A powerful form of frequency diversity)	Up to 10 dB	10%
Potential Total Improvement	**48 –67 dB**	**0.0016% - 0.00002%**

Require > 60,000 Jammers to cover Original Area

The GPS Characteristics

Characteristic		GPS/GNSS	
		Simple C/A	Directional Antenna & L1C – dual freq
System **Availability**		Worldwide	
Accuracy	Horizontal	1 to 5 meters	
	Vertical	2 to 10 meters	
Time to First Fix		~ 2 Minutes	
Vulnerability to Interference	Deliberate – 1 kW	Line of sight	1/60th of simple (~2miles)
	Natural - Iono etc.	Range errors to 10 m (?)	Dual Frequency Correction
Integrity – Probability of undetected out of spec PNT		10^{-5} (ARAIM)	10^{-7} (ARAIM + WAAS)
Cost		$20 + Display& Ant	$3000 to $20000 (?)

Inertial Navigation Systems and Components

The simple view of Inertial Navigation

- Double integrate *vector acceleration* and you have *vector position* (i.e. 3D)

$$\vec{\boldsymbol{P}} = \int\int \vec{\boldsymbol{a}}\ d^2t$$

- So with a perfect "accelerometer" you end up with perfect position… ***But*** **-**

The user has to know the Initial Position and Velocity

- So we have:

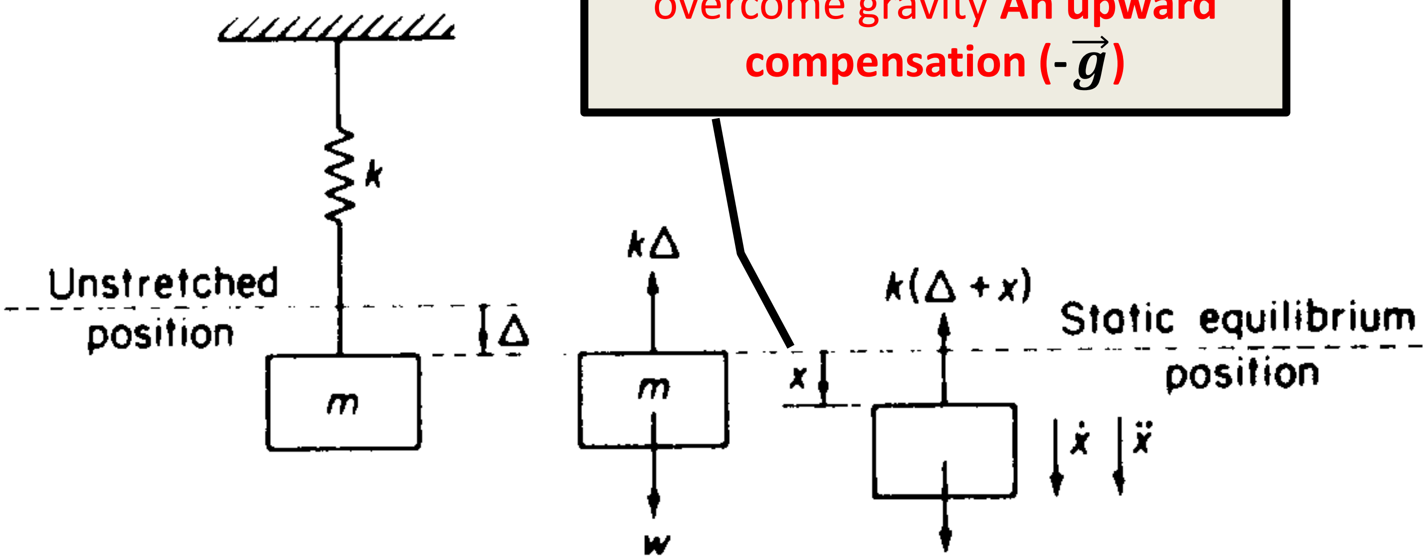
$$\vec{P} = \int\int \vec{a}\ d^2t + \overrightarrow{V_0}\,t + \vec{P}_0$$

Current position is known no better than Initial position and the error increases with time if initial velocity is not known---

Where does an inertial PNT find initial position?

"Perfect" accelerometers: What does an "Accelerometer" actually measure?

Clearly an ***un-accelerated*** "accelerometer" senses the lift to overcome gravity **An upward compensation (-$\vec{g}$)**

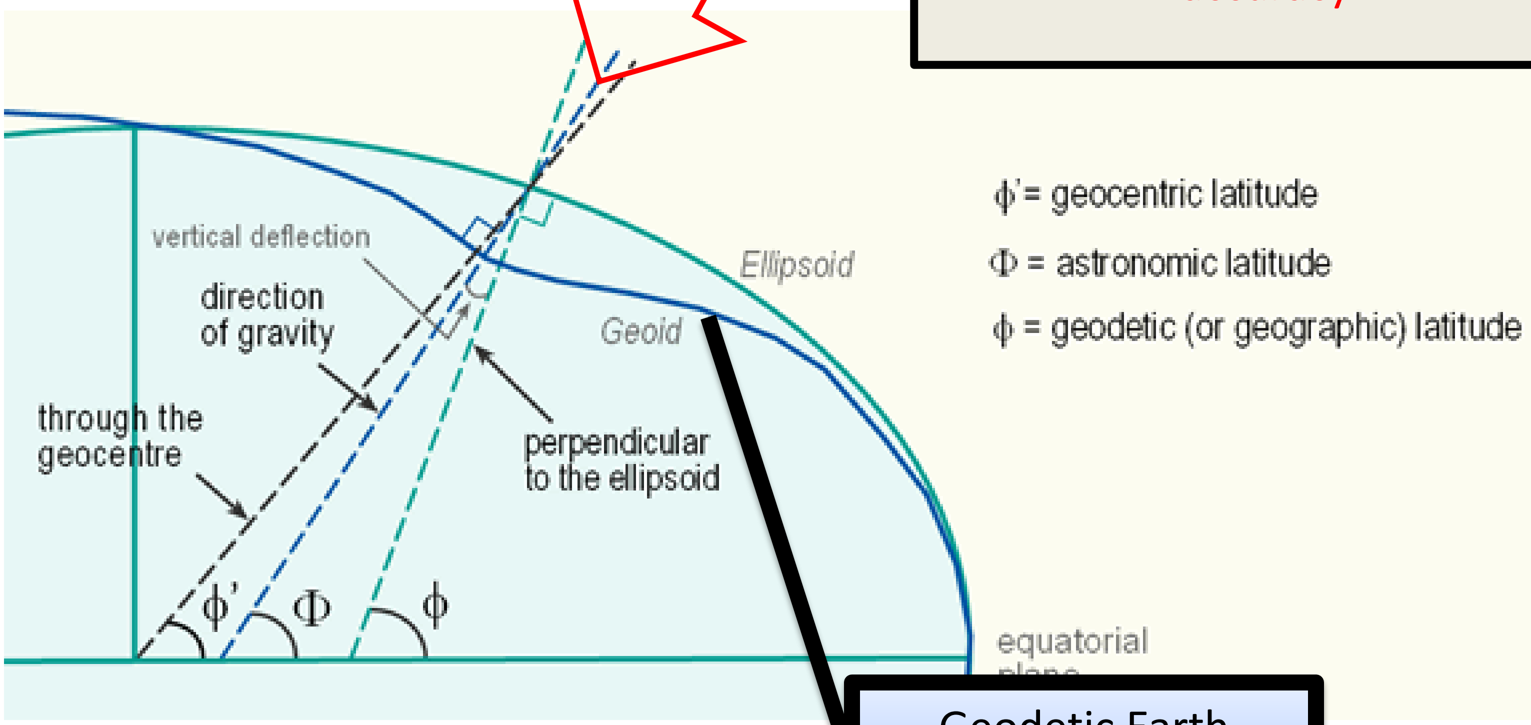


$$\vec{f} = \vec{a} - \vec{g}$$

$$\Rightarrow \quad \vec{a} = \vec{f} + \vec{g}$$

The gravity vector – “Down” is only Local

The gravity vector, near the surface, is quite quixotic for high accuracy



Geodetic Earth Surface

Another complication for inertial components

- To Navigate system must be accurately oriented to a known reference frame
- This converts the physical vectors to measurements that orient to E, N, and Up (or equivalent
- $\begin{bmatrix} P_E \\ P_N \\ P_U \end{bmatrix} = \underline{\boldsymbol{P}} = \int\int \left(\underline{\boldsymbol{f}} + \underline{\boldsymbol{g}}\right) d^2t + \underline{\boldsymbol{V}_0}\,\boldsymbol{t} + \underline{\boldsymbol{P}_0}$
- Note vector arrows have been replaced with underlines (indicating a coordinate system)

Finding Initial Attitude

- Null two cross axis accelerometers to find "level"
- Orient East/West gyro to sense no earth rate
- Typically takes 15 to 20 minutes to find orientation to about an arc minute
- **At 100km, an arc minute in azimuth is about 30 meters.**

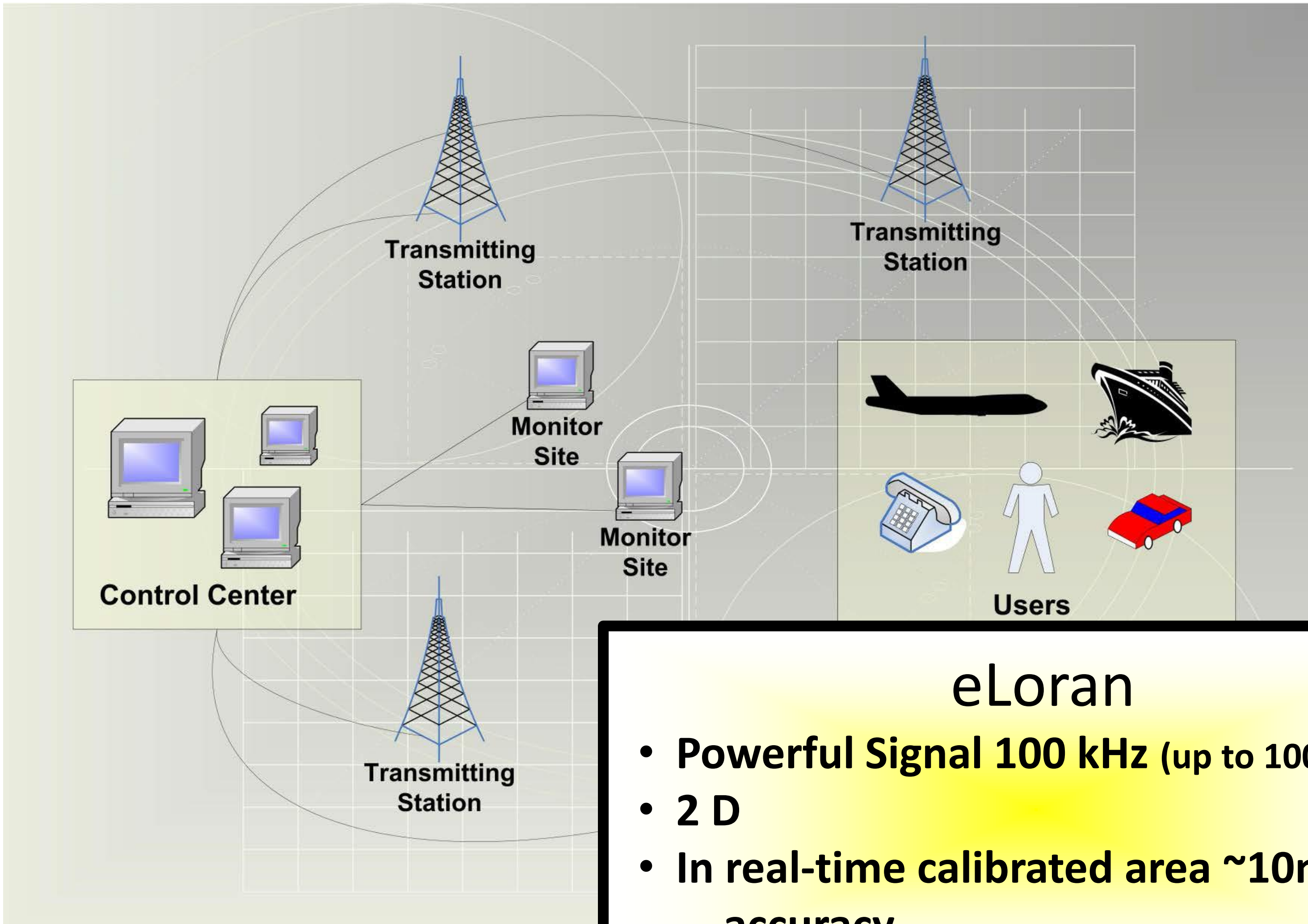
Inertials - the fundamental Challenges – even with a "perfect" accelerometer

- Initial Alignment
- Accurate knowledge of Local Gravity ($\vec{f} = \vec{a} - \vec{g}$)
- Most errors unbounded with time
- **Result - inertial horizontal *errors* :**
  - **Typically grow at 0.1 nm/hr (~ 200m/hr)**
  - **Very good ones grow at 0.01 nm/hr (~ 20m/hr)**
- And the new technology typically takes 20 years to field and is initially very expensive

Summary of Characteristics of Inertial Navigators

Characteristic		Inertials	
		Traditional Avionics	High Performance
System **Availability**		Error grows with distance and time from P_0	
Accuracy	Horizontal	>200m/hr	>20m/hr
	Vertical	No Vertical (Use Baro?)	
Time to First Fix		15 to 20 minutes	
Vulnerability to Interference	Deliberate – 1 kW	Invulnerable	
	Natural - Iono etc.	Invulnerable	
Integrity – Probability of undetected out of spec PNT		10^{-3} – (KAL007)	10^{-4} - Triple Redundant
Cost		> $5000	$200,000

eLoran Sytem Overview (courtesy UrsaNav)

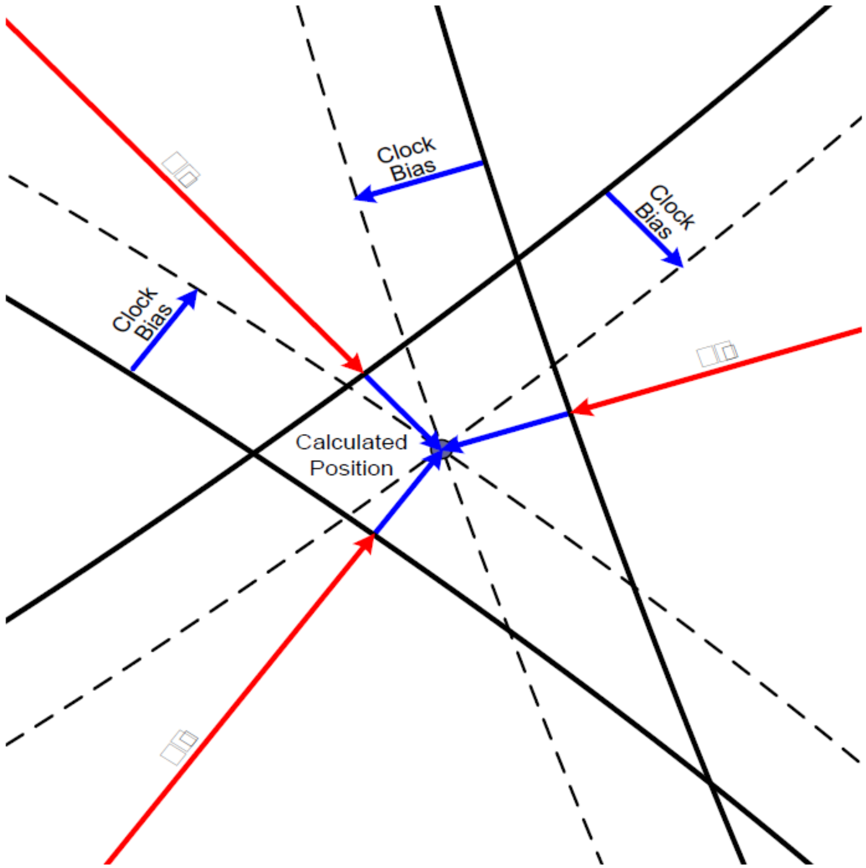


eLoran

- **Powerful Signal 100 kHz (up to 100kW)**
- **2 D**
- **In real-time calibrated area ~10m accuracy**

2D Positioning with eLoran

(Courtesy UrsaNav)



- Clock bias is common on all measured TOAs
- Clock bias is solved in position iteration process
- Three TOA measurements to solve three unknows: Latitude, Longitude and Clock bias
- Additional TOAs enable (weighted) least squares positioning

How is transmission time synchronized?

Must account for Phase lag associated with Earth and Sea conductivity

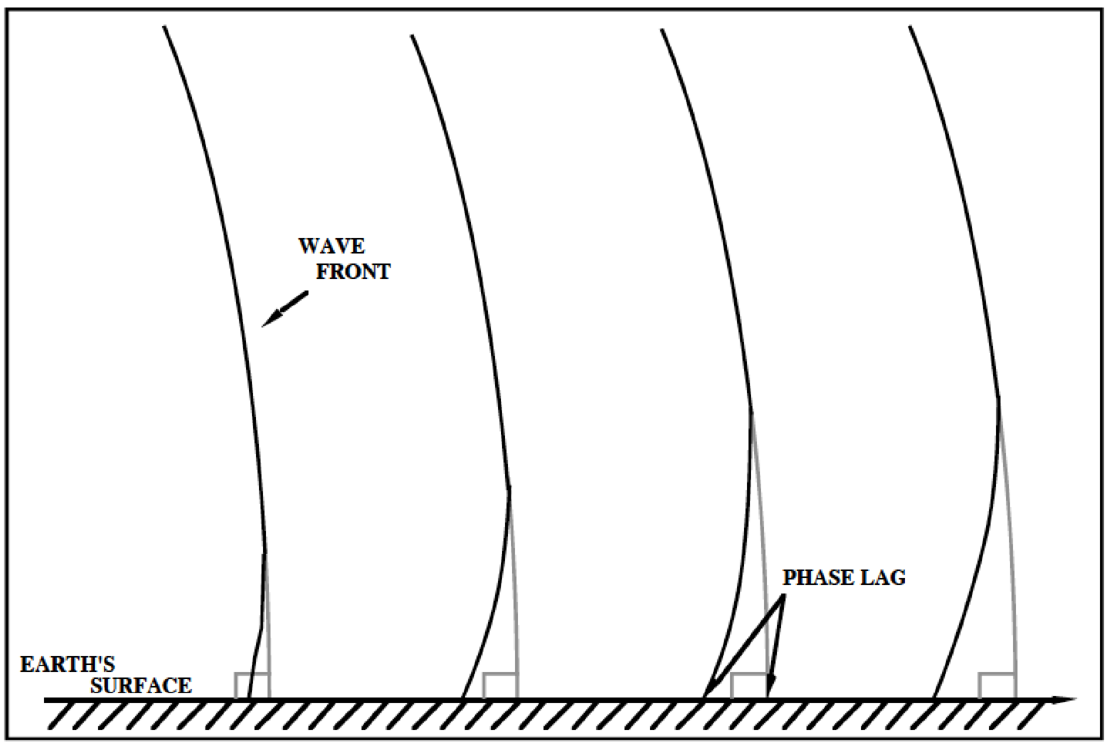


Figure 2: Loran phase lag

Basic eLoran Equation for i*th Range Measurement*

(Very similar to GPS range equation)

Measured Time of Arrival

Great Circle Range to Transmitter – **Needed to determine Position**

Additional Tailored Adjustment for particular signal path over terrain "**A**dditional **S**econdary **F**actor"

User Clock Error – common to all measurements

$$TOA_i = \frac{R_i}{c} + PF_i + SF_i + ASF_i + B + \epsilon_i$$

Actual error in Measurement and the three "Factors"

Standard Adjustment for signal delay of ***Atmosphere*** – "**P**rimary **F**actor"

Standard Adjustment for signal delay at **Sea Level over Salt Water** "**S**econdary **F**actor"

ASF Eff

Positioning System

on

At 100 Km, eLoran has substantial variability over land

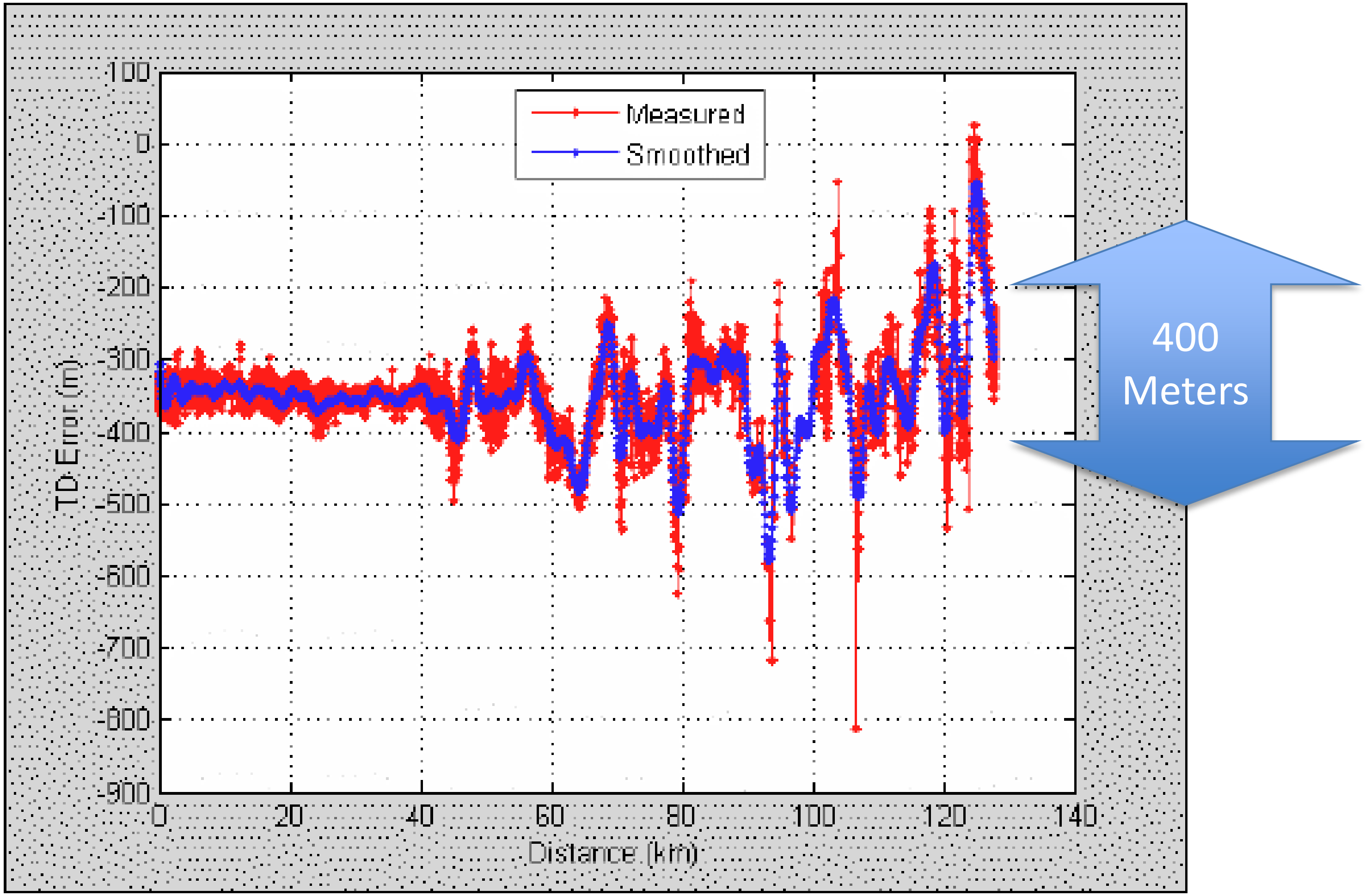
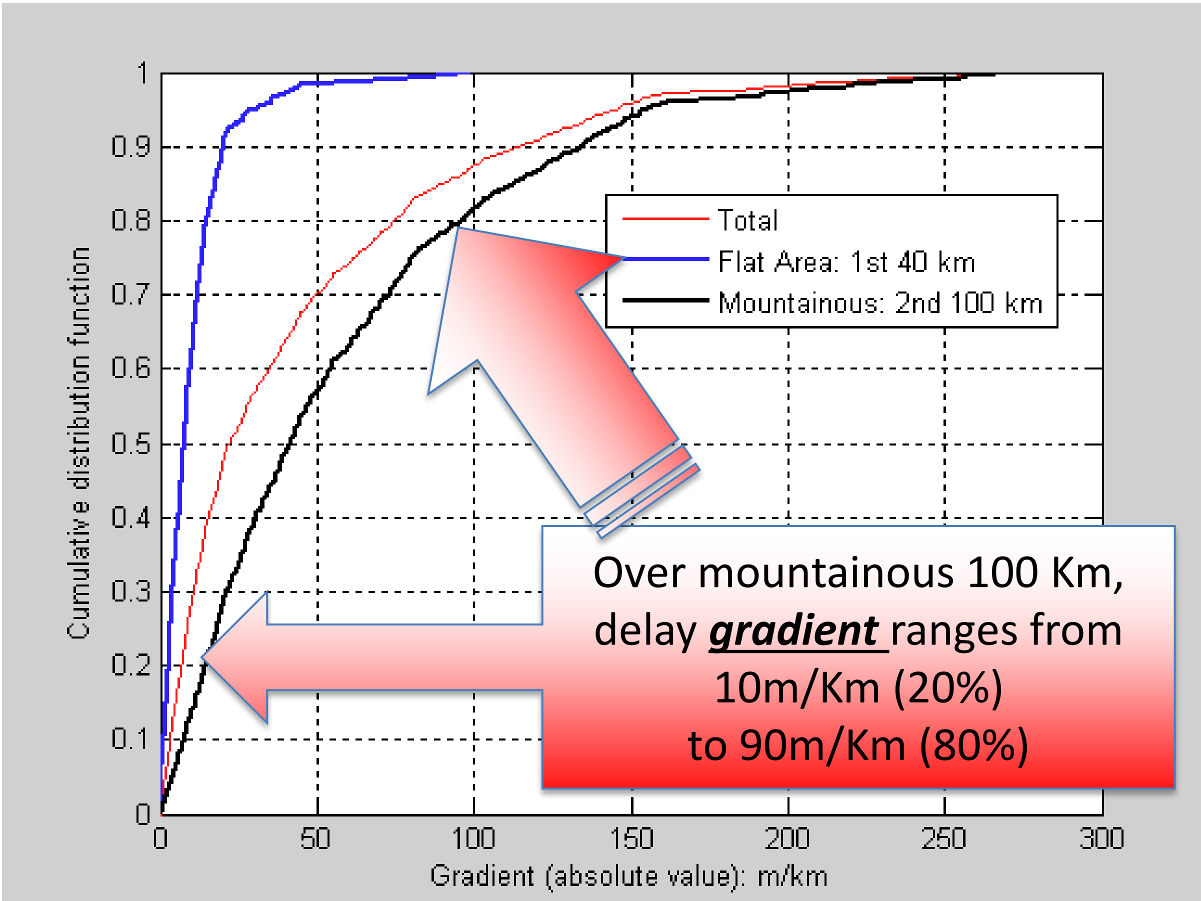
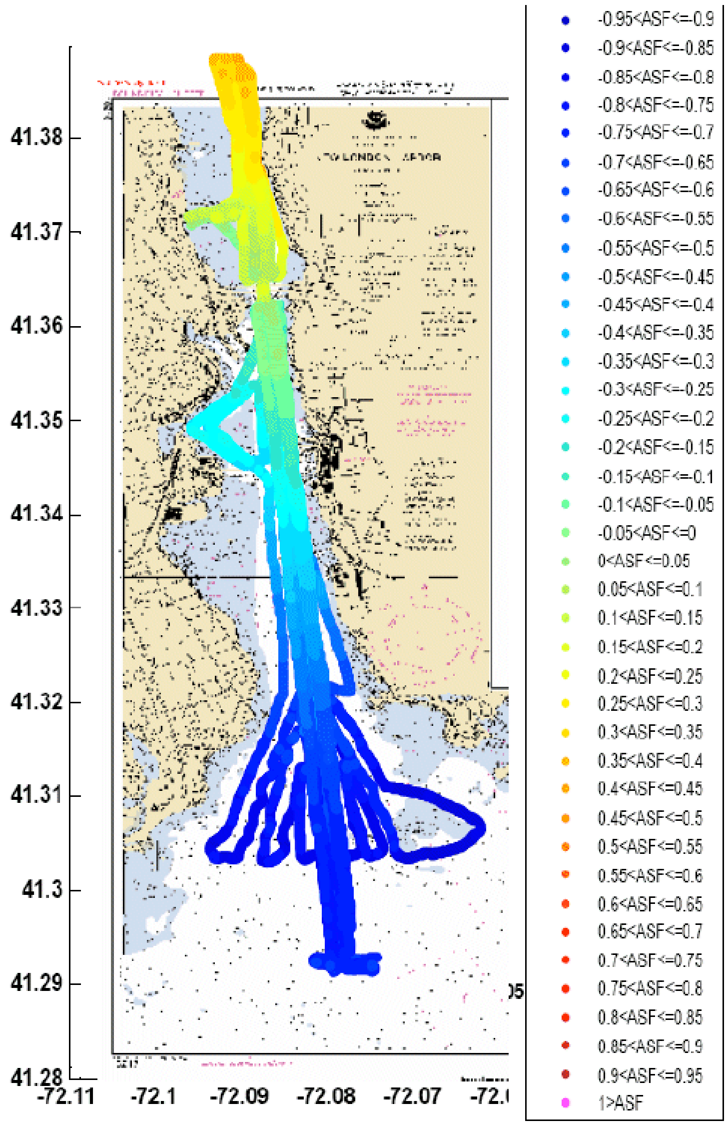


Figure 9: Raw versus smoothed TD errors

Figure 10: Cumulative distribution functions of absolute ASF spatial ***gradients***





ASF Variation as ship enters the Thames River

Variation = 1.85 μ sec
Equals 300 x 1.85 =
550 Meters

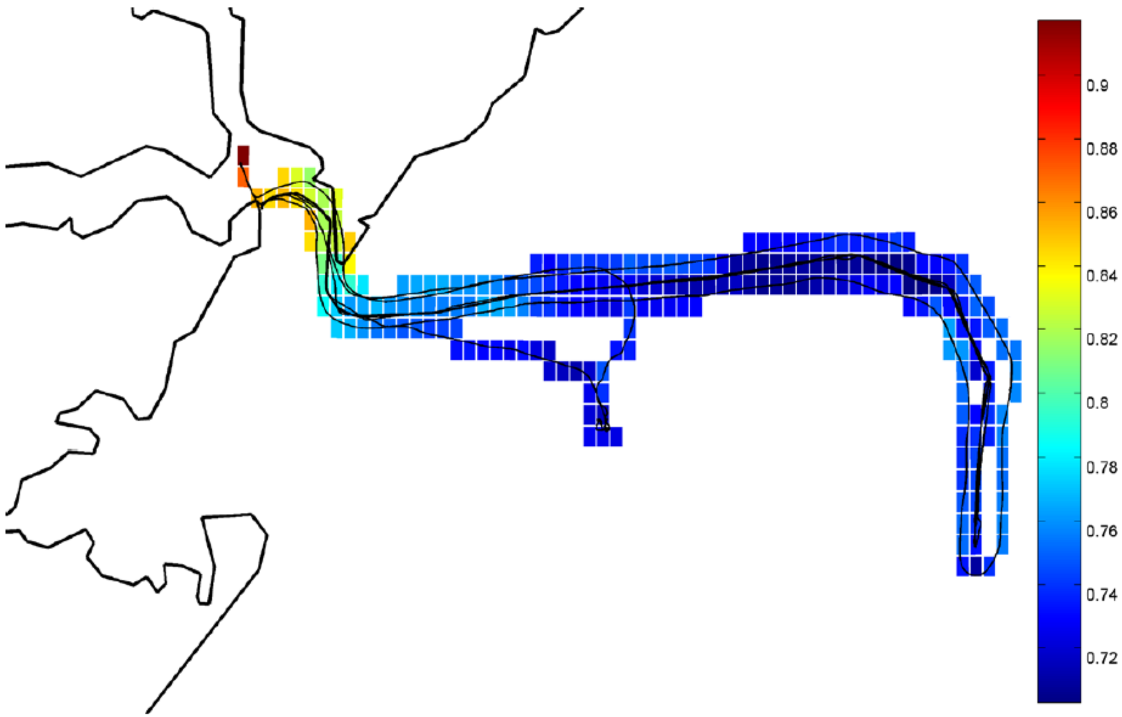
Pictures:*Johnson, Dykstra, Oates, Swaszek & Hartnett, 'Navigating Harbors at High Accuracy Without GPS: eLoran Proof-of-Concept in the Thames River', ION National Technical Meeting 2007, Session E3, Paper 5, 2007*

Technique for handling Variation in ASF

(Calibrate over terrain for each Transmitter)

- ASFs are published as a map with an ASF grid for each transmitter

picture courtesy of the General Lighthouse Authorities of the UK and Ireland



Examples of Terrain induced Variability at 600 Miles 0 to 6.6 µsec
(0 to 2000 meters)

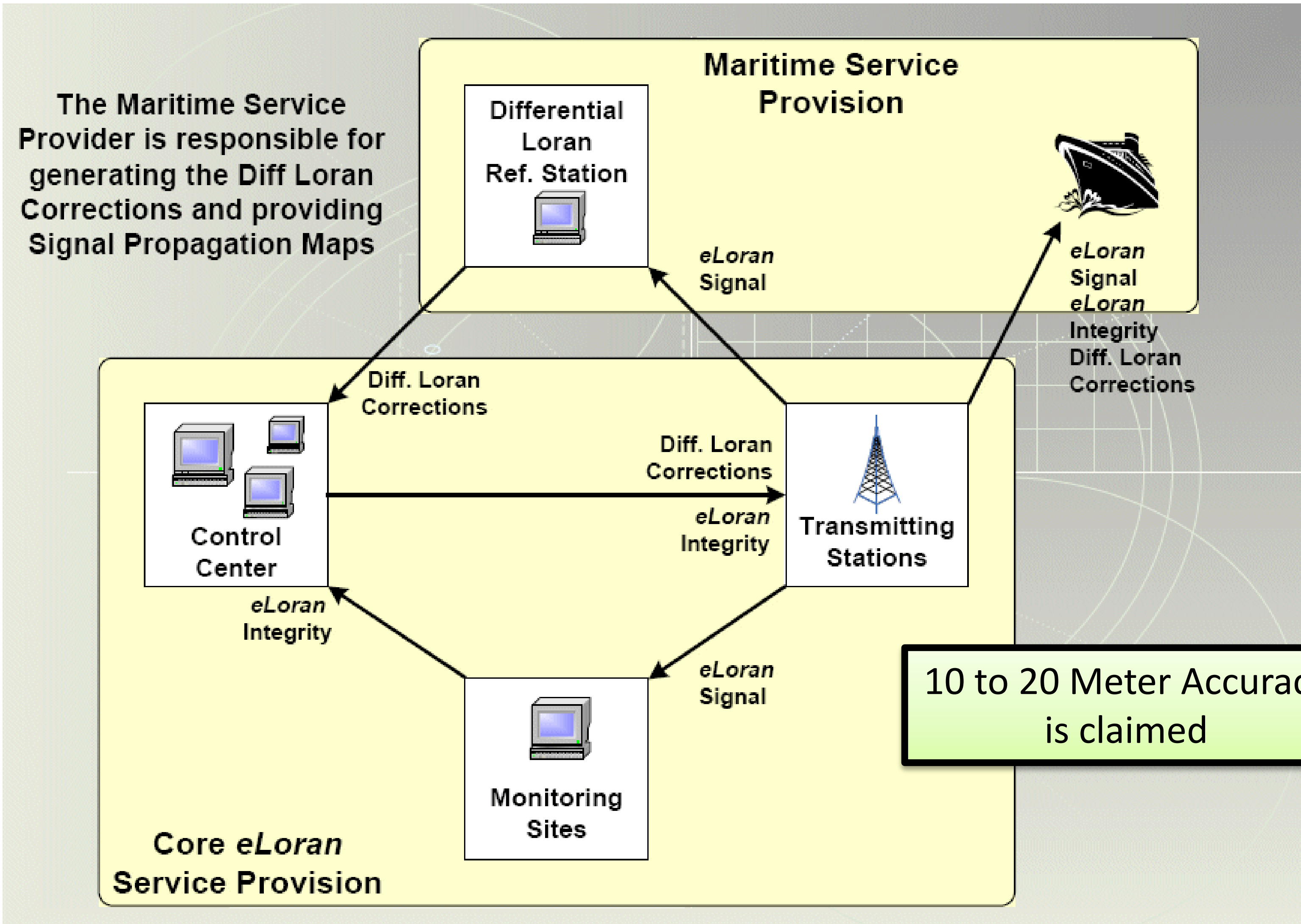
BRUNAVS' FORMULA-B PROPAGATION CALCULATION

Enter the propagation distance in kilometers: 1000

Sigma	Eps	Prop-time(us)	PF(us)	SF(us)	ASF(us)	Remarks
5	81	3338.55	3335.64	2.91	0.00	Sea-water
2E-2	15	3340.20	3335.64	2.91	1.65	Clay
1E-2	15	3340.91	3335.64	2.91	2.36	Marsh & sea-ice
2E-3	15	3343.49	3335.64	2.91	4.94	Moor
1E-3	15	3344.67	3335.64	2.91	6.12	Dry earth
5E-4	15	3345.17	3335.64	2.91	6.62	Sandy desert
1E-4	15	3344.16	3335.64	2.91	5.61	Snow and ice

Differential eLoran

Improves Accuracy in a limited region



10 to 20 Meter Accuracy is claimed

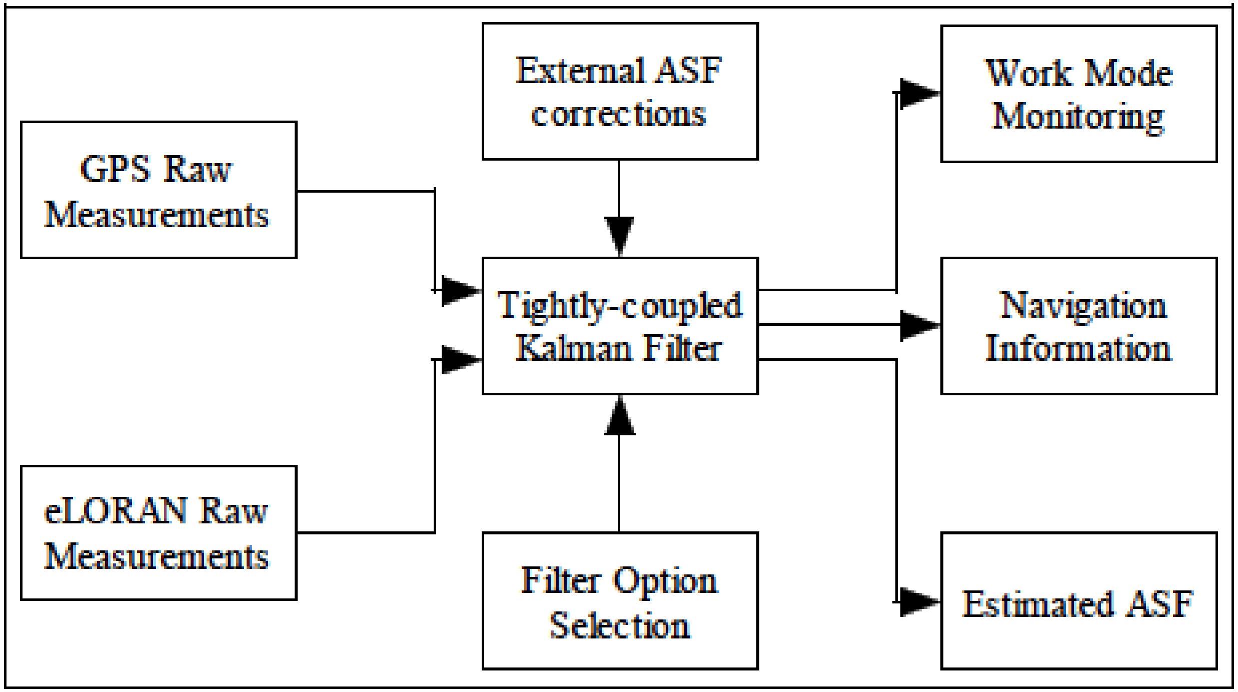


Figure 11: Structure of an integrated GPS/eLORAN system

eLoran Accuracy

- Good News – Differential Technique can improve accuracy to ~20 meters or better
- Less Good News – Corrections typically only help in small area, like a harbor – no analogy to WAAS corrections
- Good news – GPS can provide continuous corrections, and then user can 'Flywheel" through brief outages of GPS using eLoran

$$TOA_i = \frac{s_i}{c} + PF_i + SF_i + \boxed{ASF_i + B + \epsilon_i} + \gamma_i$$

GPS Correction

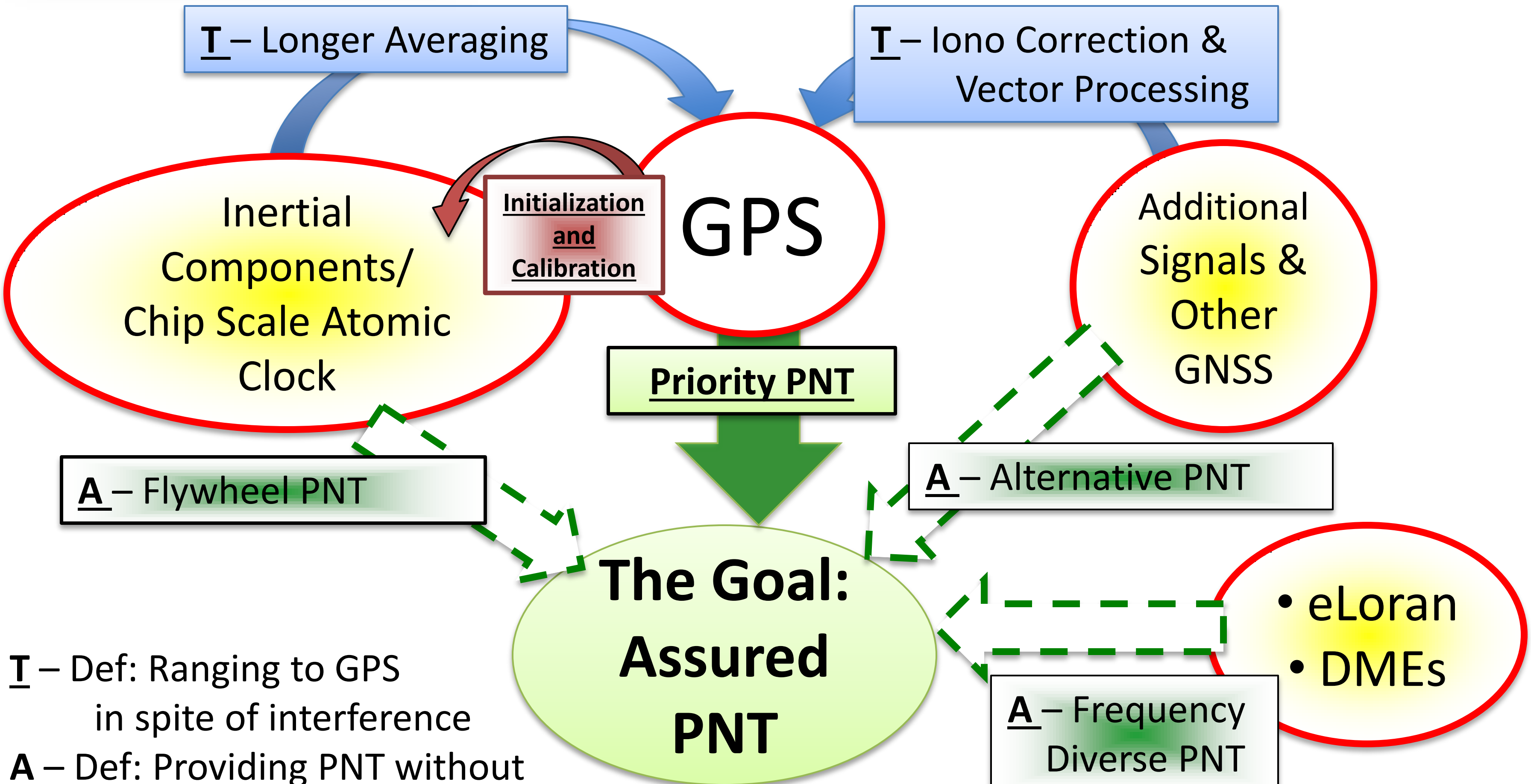
Summary of eLoran Charcteristics

Characteristic		eLoran: Non-Differential	eLoran: Differential
System **Availability**		Regional	Local – e.g. Harbor Area
Accuracy	Horizontal	30m to >200m	10m to 20m
Accuracy	Vertical	No Vertical (Use Baro?)	No Vertical (Use Baro?)
Time to First Fix		1 to 2 Minutes (?)	1 to 2 Minutes (?)
Vulnerability to Interference	Deliberate – 1 kW	Nearly Invulnerable	Nearly Invulnerable
Vulnerability to Interference	Natural - Iono etc.	Nearly Invulnerable	Nearly Invulnerable
Integrity – Probability of undetected out of spec PNT		10^{-3}	10^{-4}
Cost		$20 + Display& Ant	$20 + Display& Ant

Grand Synergy

Assured Availability of PNT - "PTA"

Preamble to **T**oughening and **A**ugmenting The Synergies



T – Def: Ranging to GPS in spite of interference

A – Def: Providing PNT without range to GPS (could be Sky-impaired or Signal-denied)

Characteristic		GPS/GNSS + IMU + eLoran
System **Availability**		Worldwide
Accuracy	Horizontal	1 to 5 meters
	Vertical	2 to 10 meters
Time to First Fix		~ 2 minutes
Vulnerability to Interference	Deliberate – 1 kW	Grows at ~20m/hr
	Natural - Iono etc.	OK in Temperate zones
Integrity – Probability of undetected out of spec PNT		10^{-7} (ARAIM + WAAS)
Cost		?

Synergy

The Grand Comparison

Characteristic		GPS/GNSS		Inertials		eLoran		GPS/GNSS + IMU + eLoran
		Simple C/A	Directional Antenna & L1C – dual freq	Traditional Avionics	High Performance	Non-Differential	Differential	
System **Availability**		Worldwide		Error grows with distance and time from P_0		Regional	Local – e.g. Harbor Area	Worldwide
Accuracy	Horizontal	1 to 5 meters		>200m/hr	>20m/hr *	30m to >200m	10m to 20m	1 to 5 meters
	Vertical	2 to 10 meters		No Vertical (Use Baro?)		No Vertical (Use Baro?)		2 to 10 meters
Time to First Fix		~ 2 Minutes		15 to 20 minutes		1 to 2 Minutes (?)		~ 2 minutes
Vulnerability to Interference	Deliberate – 1 kW	Line of sight	1/60th of simple (~2miles)	Invulnerable		Nearly Invulnerable		Grows at ~20m/hr
	Natural - Iono etc.	Range errors to 10 m (?)	Dual Frequency Correction	Invulnerable		Nearly Invulnerable		OK in Temperate zones
Integrity – Probability of undetected out of spec PNT		10^{-5} (ARAIM)	10^{-7} (ARAIM + WAAS)	10^{-3} – (KAL007)	10^{-4} - Triple Redundant	10^{-3}	10^{-4}	10^{-7} (ARAIM + WAAS)
Cost		$20 + Display& Ant	$3000 to $20000 (?)	> $5000	$200,000	$20 + Display& Ant	20 + Display& Ant	?

Even Perfect "Accelerometers" can only be perfect *non-field force* sensors They sense $\vec{f}$ not $\vec{a}$

$$\vec{f} = \vec{a} - \vec{g}$$

- So system has to accurately know $\vec{g}$
- Initial Alignment errors within "local" coordinate frame propagates errors
- Inertials are unstable sensors of altitude

Autonomous Driving

Google's modified Toyota Prius uses an array of sensors to navigate public roads without a human driver. Other components, not shown, include a GPS receiver and an inertial motion sensor.

LIDAR
A rotating sensor on the roof scans more than 200 feet in all directions to generate a precise three-dimensional map of the car's surroundings.

POSITION ESTIMATOR
A sensor mounted on the left rear wheel measures small movements made by the car and helps to accurately locate its position on the map.

VIDEO CAMERA
A camera mounted near the rear-view mirror detects traffic lights and helps the car's onboard computers recognize moving obstacles like pedestrians and bicyclists.

RADAR
Four standard automotive radar sensors, three in front and one in the rear, help determine the positions of distant objects.

Source: Google

THE NEW YORK TIMES; PHOTOGRAPHS BY RAMIN RAHIMIAN FOR THE NEW YORK TIMES

"There are approximately 3.5 million professional truck drivers in the United States, according to estimates by the American Trucking Association. "

Robotic Trucks are coming

- Productivity Savings: Robotic Mining Trucks in Australia
- But…

- $\overrightarrow{\boldsymbol{P}} = \int\int(\overrightarrow{\boldsymbol{f}} + \overrightarrow{\boldsymbol{g}})\ d^2t + \overrightarrow{\boldsymbol{V_0}}\,\boldsymbol{t} + \overrightarrow{\boldsymbol{P}}_0$

$$\vec{\boldsymbol{P}} = \iint \vec{\boldsymbol{a}}\; d^2t + \overrightarrow{\boldsymbol{V}_0}\, \boldsymbol{t} + \vec{\boldsymbol{P}}_0$$

$$\vec{\boldsymbol{a}} = \vec{\boldsymbol{f}} - \vec{\boldsymbol{g}}$$

$$\vec{\boldsymbol{P}} = \iint (\vec{\boldsymbol{f}} - \vec{\boldsymbol{g}})\; d^2t + \overrightarrow{\boldsymbol{V}_0}\, \boldsymbol{t} + \vec{\boldsymbol{P}}_0$$

$$\vec{a} = \vec{f} - \vec{g}$$