PNTAB:
Assured PNT - Strengths and Synergies and Future Plans

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PNTAB Charter

The National, Space-Based, Positioning, Navigation, and Timing (PNT) Advisory Board (**PNTAB**) provides:

- ***Independent*** advice to the U.S. government on GPS-related
  - *policy,*
  - *planning,*
  - *program management, and*
  - *funding profiles*

In relation to the current state of national ***and international satellite navigation services***.

- Fundamental Purpose:

  Assured PNT **(At required availability, accuracy and integrity)**

◆ PNTAB Generally meets 1 to 2 times per year.

- **Recent well-intended statement :**

" The result would be a GPS of things – akin to the Internet of things – where objects, including our military systems, ***keep track of their position, orientation, and time from the moment they are created with no need for updates from satellites***."

Perhaps better said…

- ***To Assure PNT*** **– the PTA solution:**

"We must ***P***rotect, ***T***oughen, and ***A***ugment GPS to ensure that it ***continues to provide Economic and Societal Benefits***"

Current PNTAB Assessment:

"No *current* or *foreseeable* alternative to GNSS (Primarily GPS) can deliver equivalent accuracy (to millimeters, 3D) and world wide 24/7 availability"

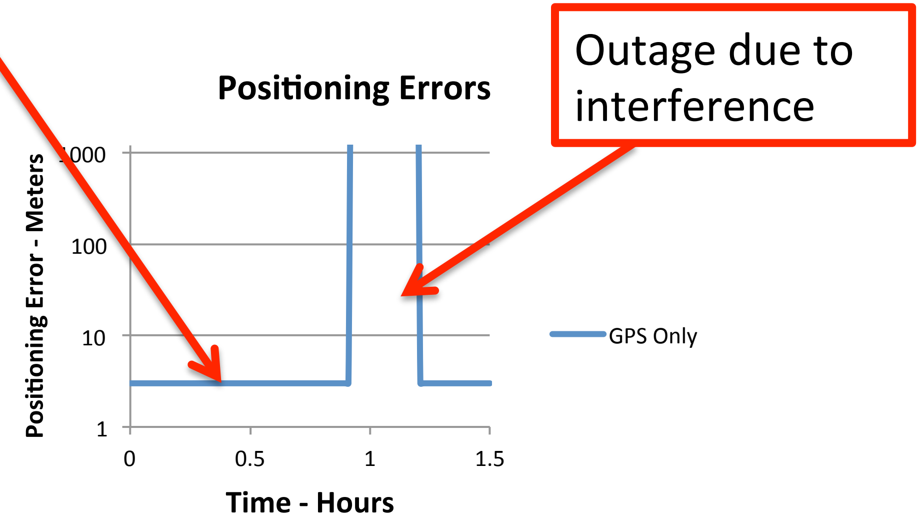
Augment: **A Review-** Strengths and Synergies

- GPS/GNSS
- Inertial Systems and Components
- eLoran

GPS/GNSS Situation Summary

Characteristic	GPS/GNSS Simple Civil Set
System Availability	Worldwide
Accuracy	1 to 5 meters
Time to First Fix	~ 2 Minutes
Vulnerability to Deliberate – 1 kW Interference.	**About 150 Miles**
Cost	$20 + Display& Ant

- Susceptibility to interference ***can be virtually eliminated with inexpensive inertial navigator and directional antennas***
- Costs to toughen and augment are dropping



Inertial Systems and Components Strengths and Synergies

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*** -

Complication #1

User requires ***Initial Position*** and ***Velocity***

- So we have:

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

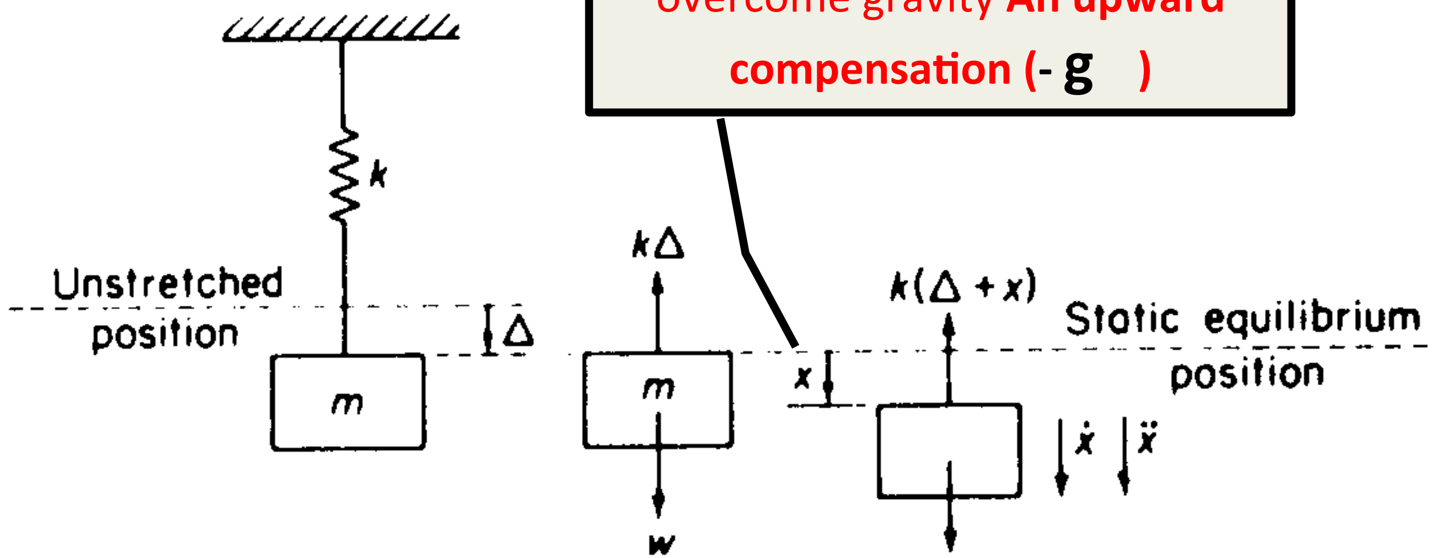
Current position is known no better than Initial position and the error increases with time if initial velocity is not known---

Where does an inertial PNT find initial position?

(Hint: Usually GPS!)

Complication #2 - "Perfect" accelerometers: What does an "Accelerometer" actually measure?

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



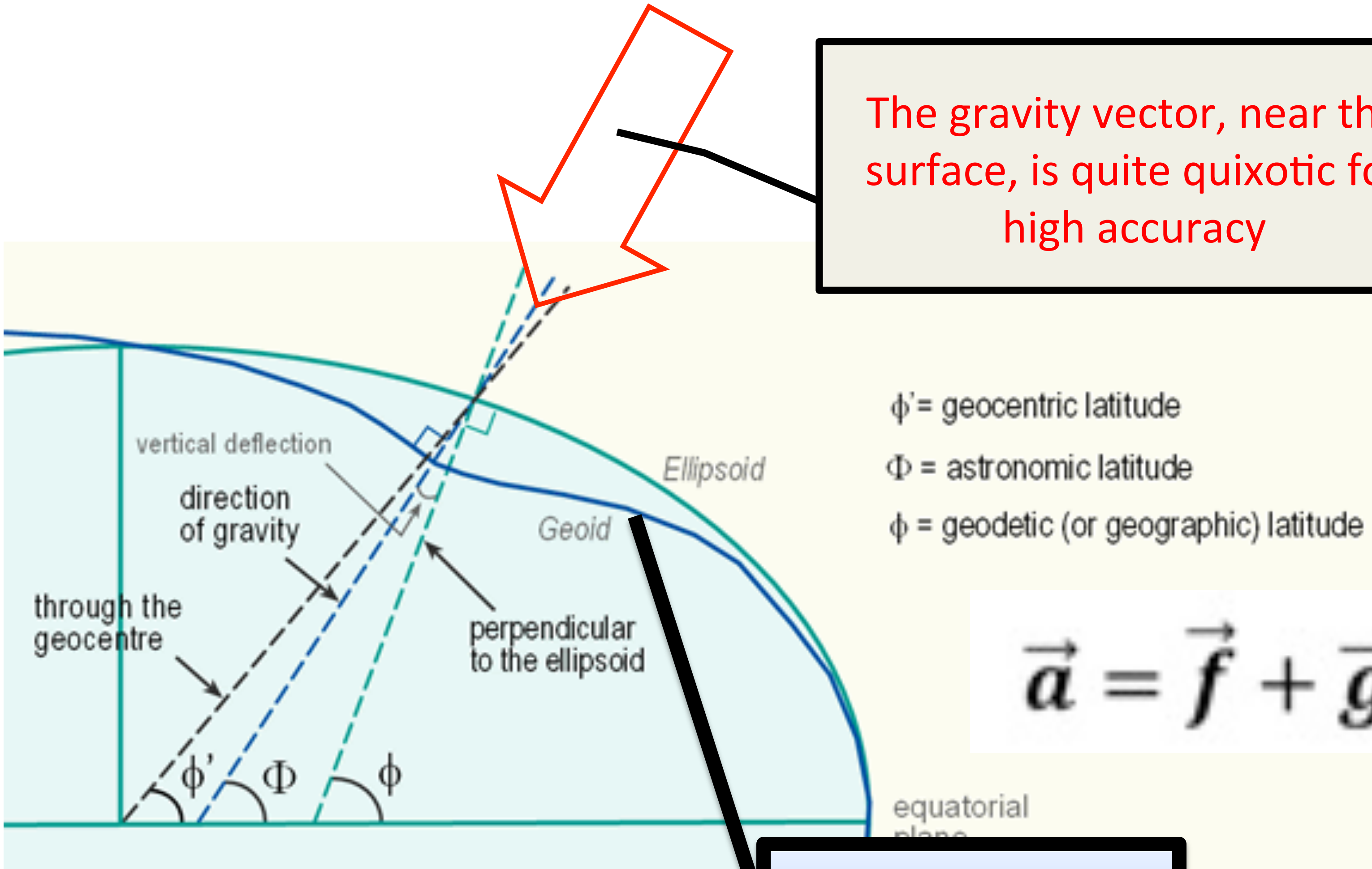
Doc Draper, the Father of Inertial Navigation always called these Devices "***Specific Force Receivers***"

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

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

The gravity vector – “Down” is only Local

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



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

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 – User Stationary
(either physical rotation or "strap-down")

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

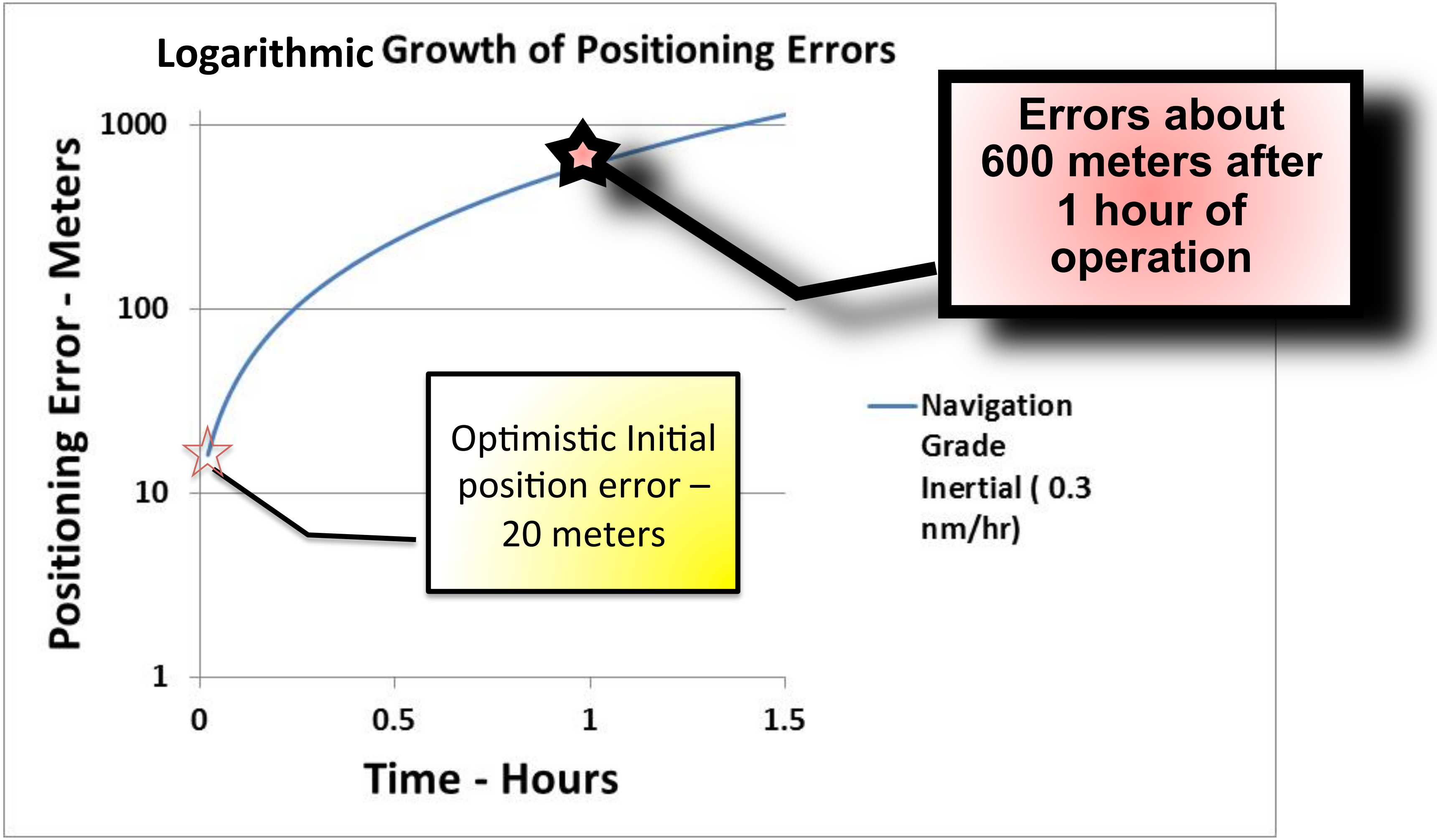
Note: **With GPS aiding, initial alignment can occur in the first 30 minutes of flight with no waiting on the flight line. During flight, biases can be calibrated**

Maintaining Orientation - ***Gyroscopes***

- Inertial Quality Gyros : 0.1 – 0.001 deg/hr
- In one hour drift 6 arc minutes down to 0.06 arc minutes.
- At 1000 km, angles equivalent to 1700 meters down to 17 meters.

The Points:
- Even very good Gyroscopes cannot hold attitude induced errors to GPS levels after a few hours of travel.
- All instruments must be aligned to the common coordinate frame

Summary: Hi Performance Inertial Navigator (error growth at 0.3 nm/hour)



Wrap-up: 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 PNT system has to accurately know $\vec{g}$
- Initial Alignment errors within "local" coordinate frame propagates errors
- Inertials are unstable sensors of ***altitude*** – i.e. 2 Dimensional only

For fully robust receivers, all approaches benefit enormously with GNSS as an essential part

Key Inertial Systems Characteristics

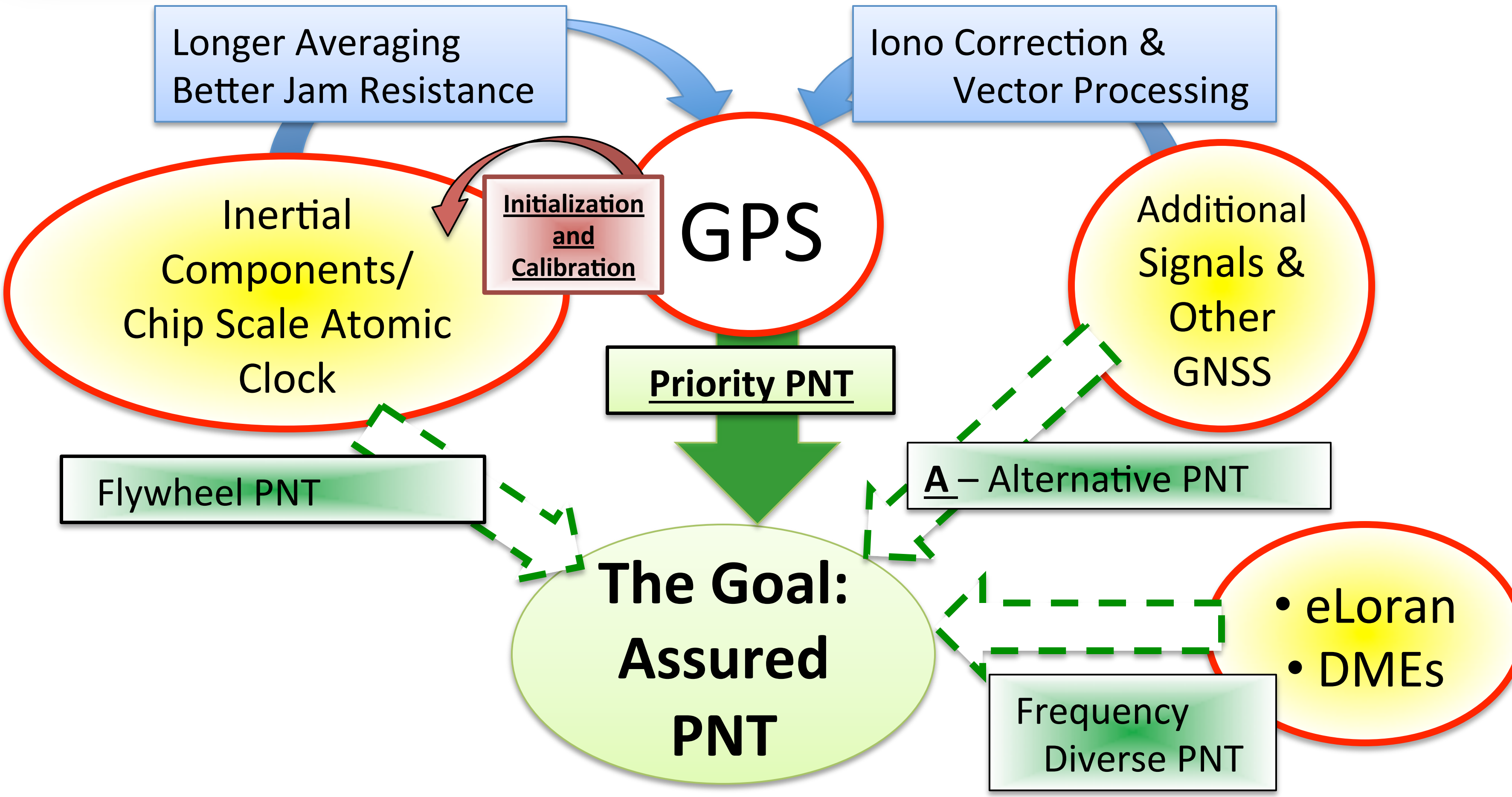
Characteristic		Top Grade Inertial Navigator
System **Availability**		Worldwide *when Initialized*
Accuracy	**Horizontal**	20 meters (?) + **300 Meters/Hr.**
	Vertical	**No vertical**
Time to First Fix		**15 to 20 Minutes**
Vulnerability to Deliberate – 1 kW Interference		**Not Jammable**
Cost		$100K

- **Initial Alignment**. Both a time and an accuracy problem. Requires at least 15 minutes (unaided) to align to a local reference frame
- **Initial Position**. Accuracy is no better than initial knowledge of position (and Velocity!)
- **No Altitude**. The third dimension is inherently unstable.
- **Errors unbounded** -grow with time and time squared.
- **Accelerometers only measure part of acceleration**. Must know gravity direction and magnitude.

Promising new DARPA Devices will not fix these weaknesses and are at least 15 years away…

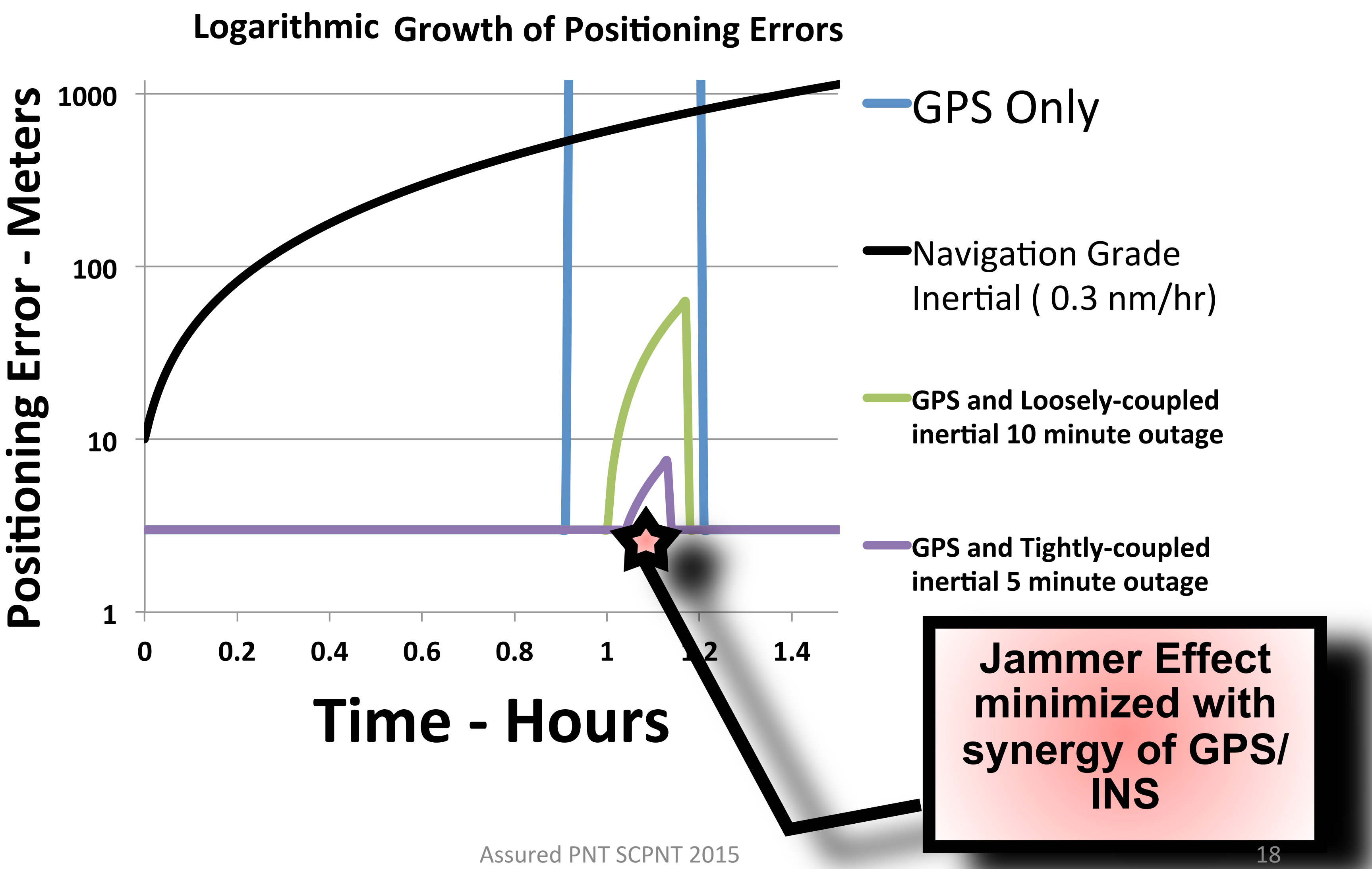
Assured Availability of PNT - "PTA"

Synergy Level 2 – Tightly coupled GPS Inertial



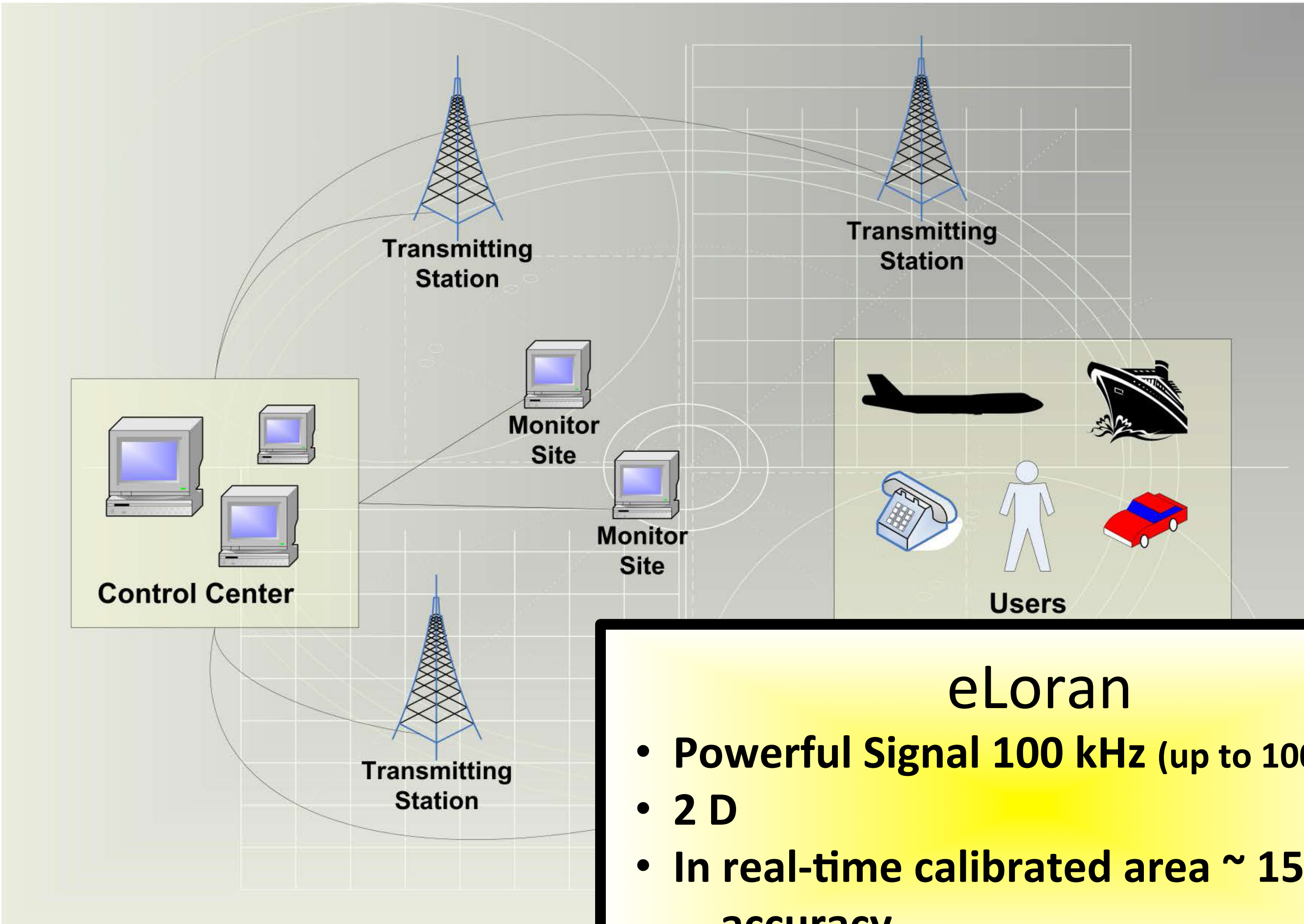
Summary: Synergy of GPS/Inertial

Augmentation Provides Manageable errors



eLoran
Strengths and Synergies

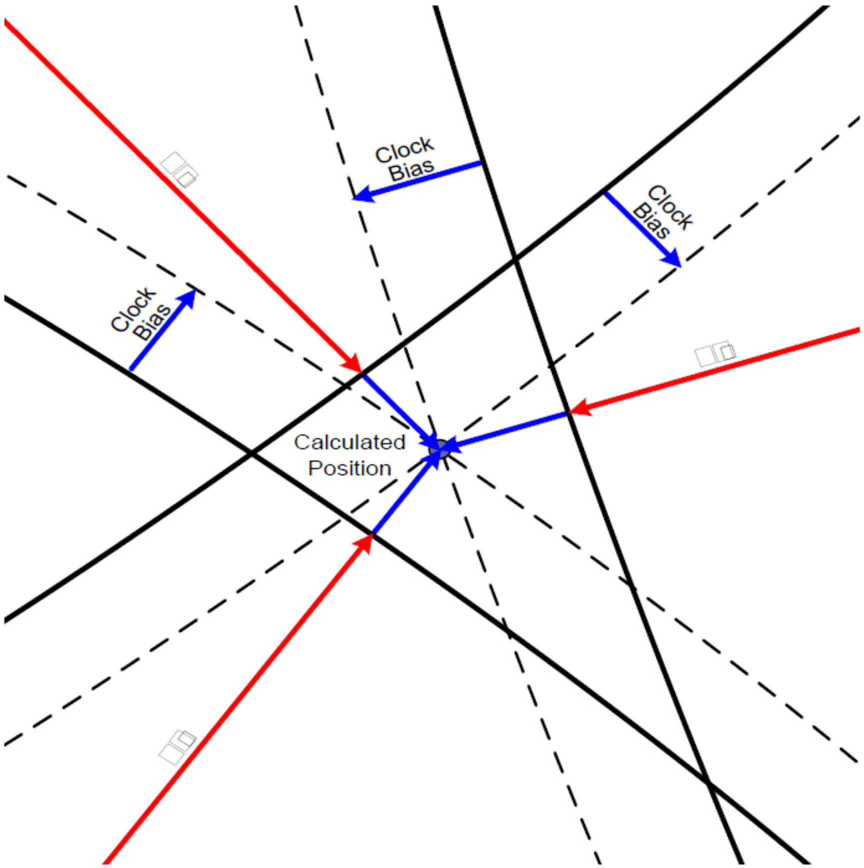
eLoran Sytem Overview (courtesy UrsaNav)



eLoran

- **Powerful Signal 100 kHz (up to 100kW)**
- **2 D**
- **In real-time calibrated area ~ 15m 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

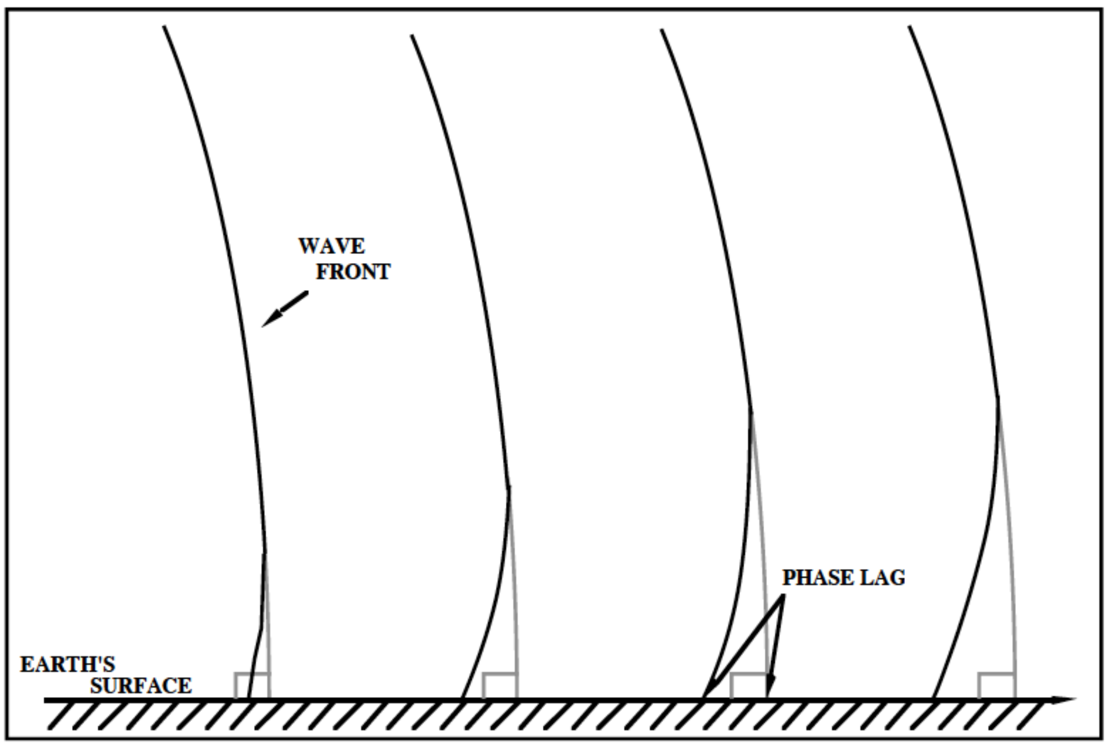


Figure 2: Loran phase lag

Basic eLoran Equation for i*th Range Measurement*

(Very similar to GPS range equation)

$$TOA_i = R_i / c + PF_i + SF_i + ASF_i + B + \epsilon_i$$

- 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 Bias– common to all measurements
- 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"
- **Actual error** in Measurement and the three "Factors"

At 100 Km, eLoran has substantial variability over land

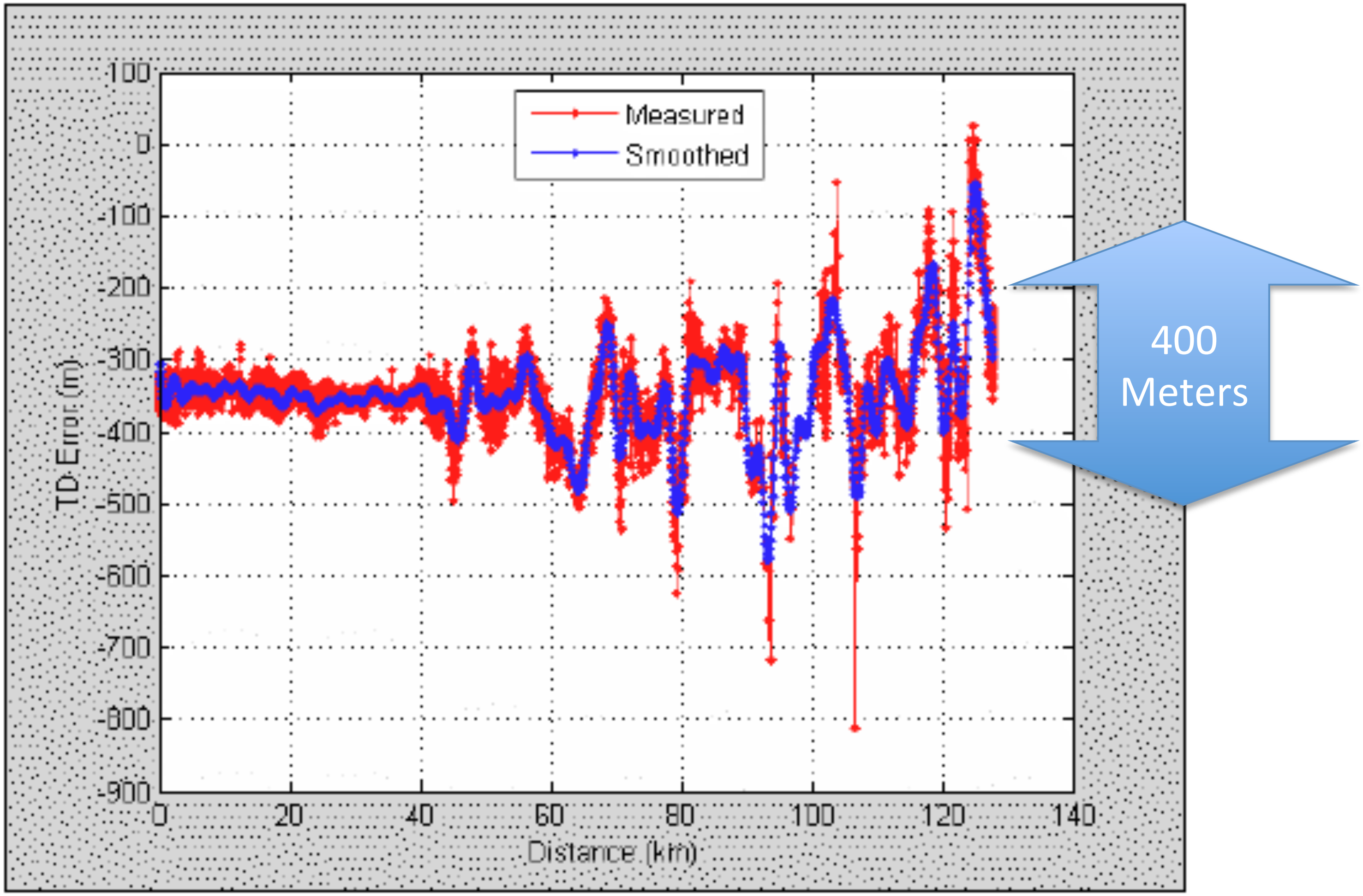
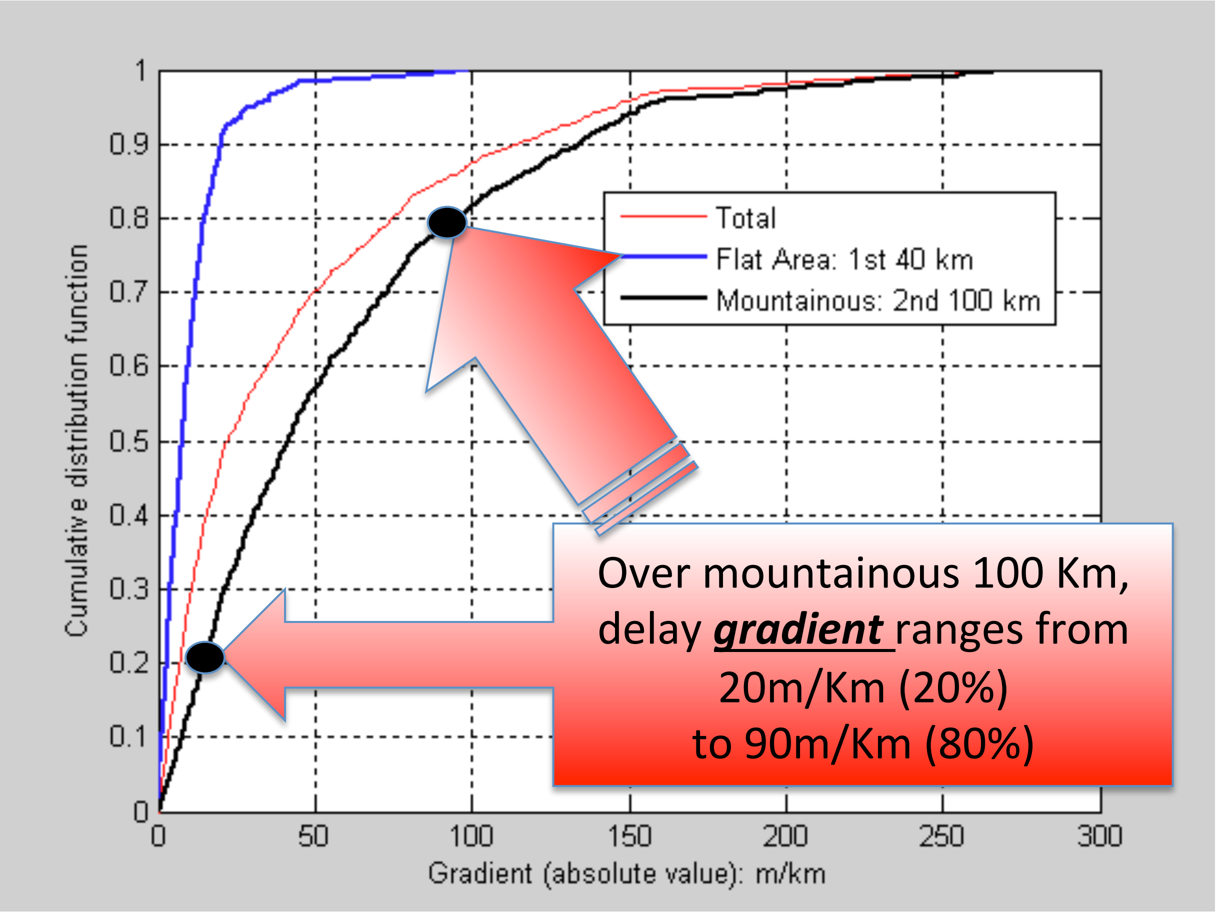
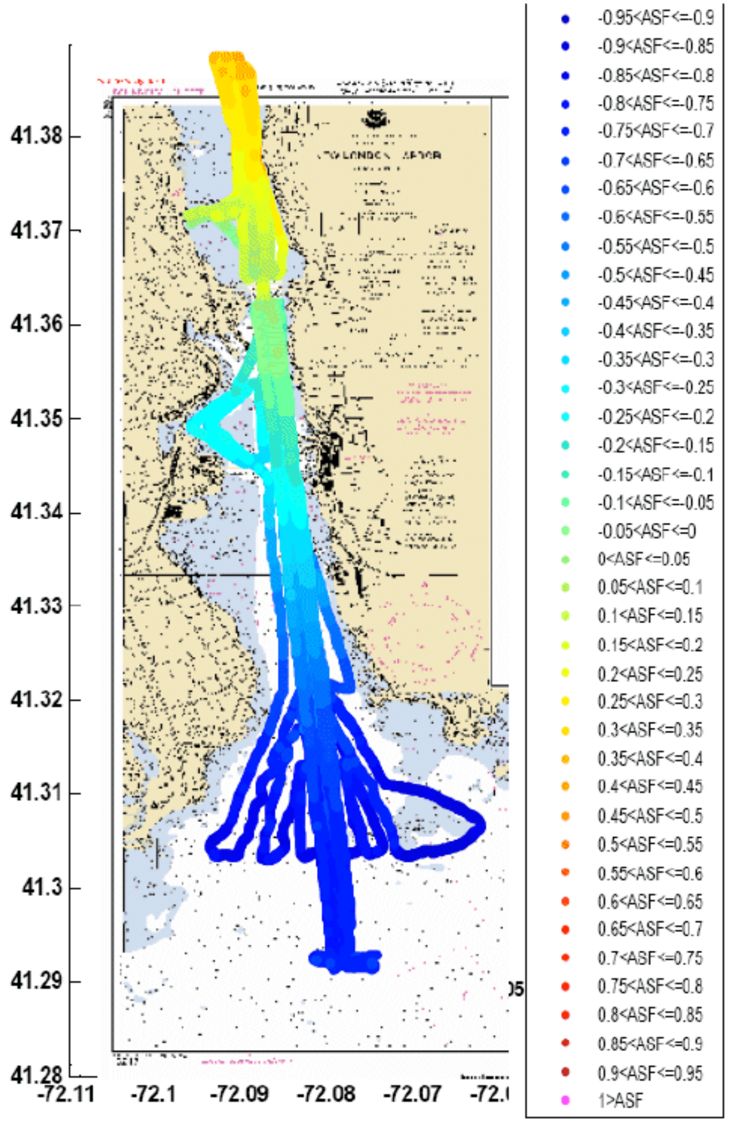


Figure 9: Raw versus smoothed TD errors

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



ASF Variation as ship enters the Thames River



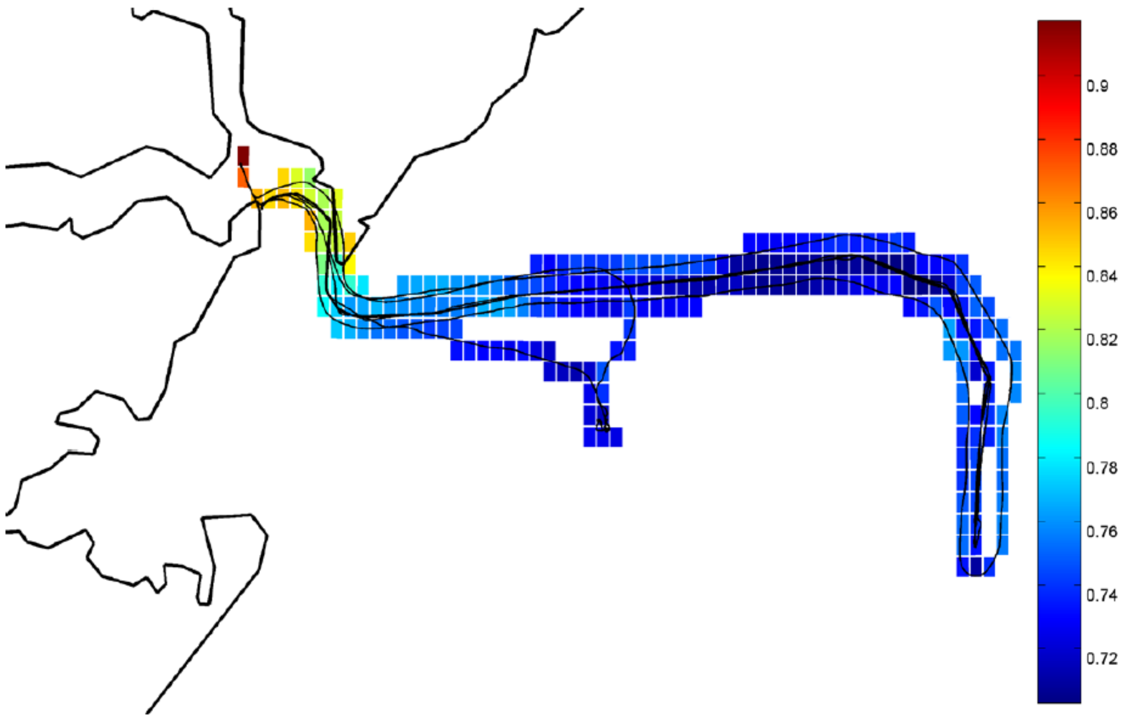
Variation = 1.85 μ sec
Equals 300 x 1.85 =
550 Meters

***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)

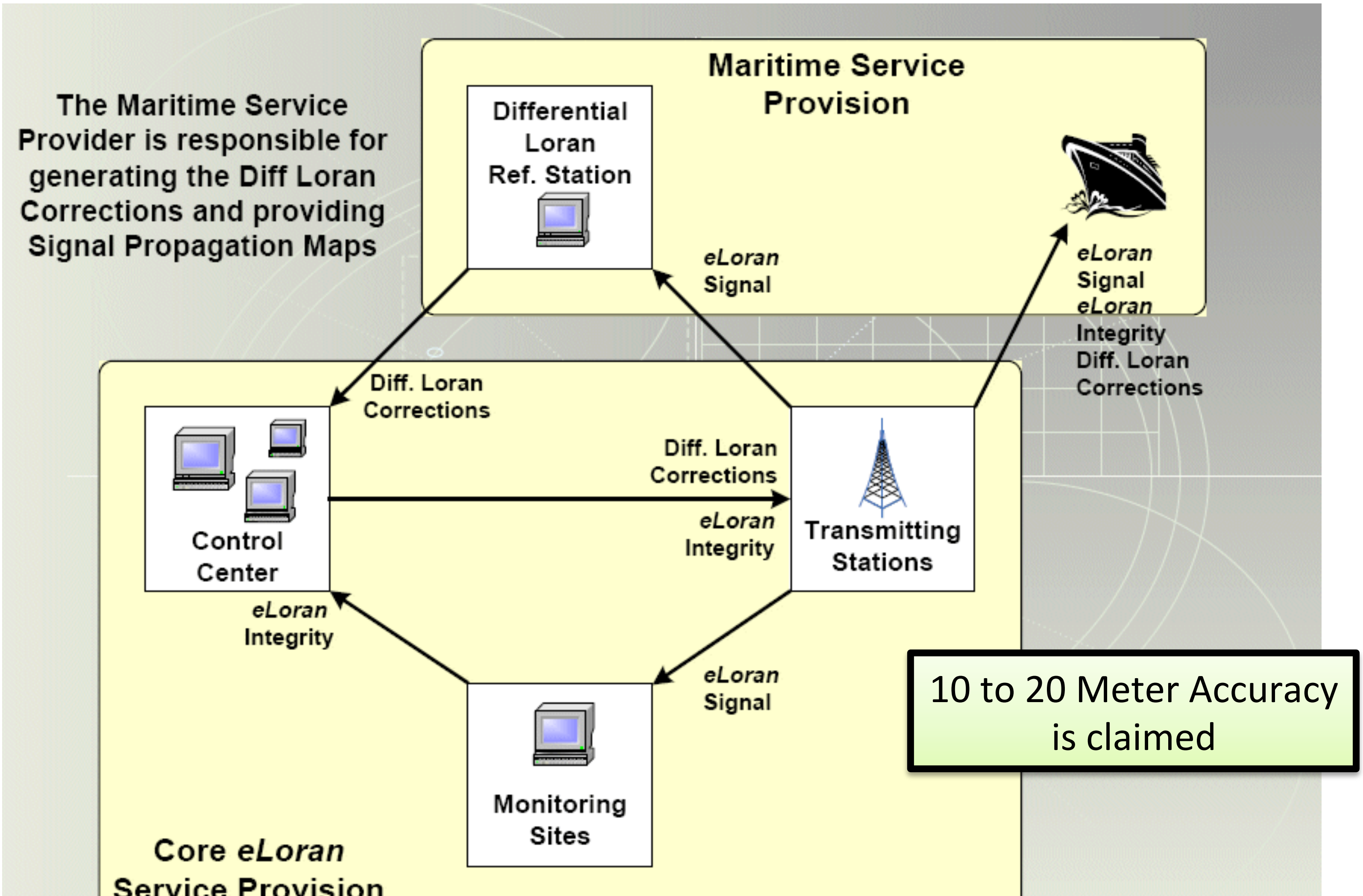
- ASFs are published as a map with an ASF grid for each transmitter

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



Differential eLoran

Improves Accuracy in a limited region



eLoran Characteristics

- **Unjammable**. (virtually)
- **Regional –** But not currently deployed
- **Horizontal Only**. No third dimension
- **Accuracy over landmass subject to large errors** Variable speed of signal – errors can be ¼ mile or more
- **Can Achieve 15 meter accuracy in small areas** (within about 5 miles of calibration point) must use *continuous updates* of Differential Accuracy

For Assured PNT – an ***integrated*** GPS and eLoran

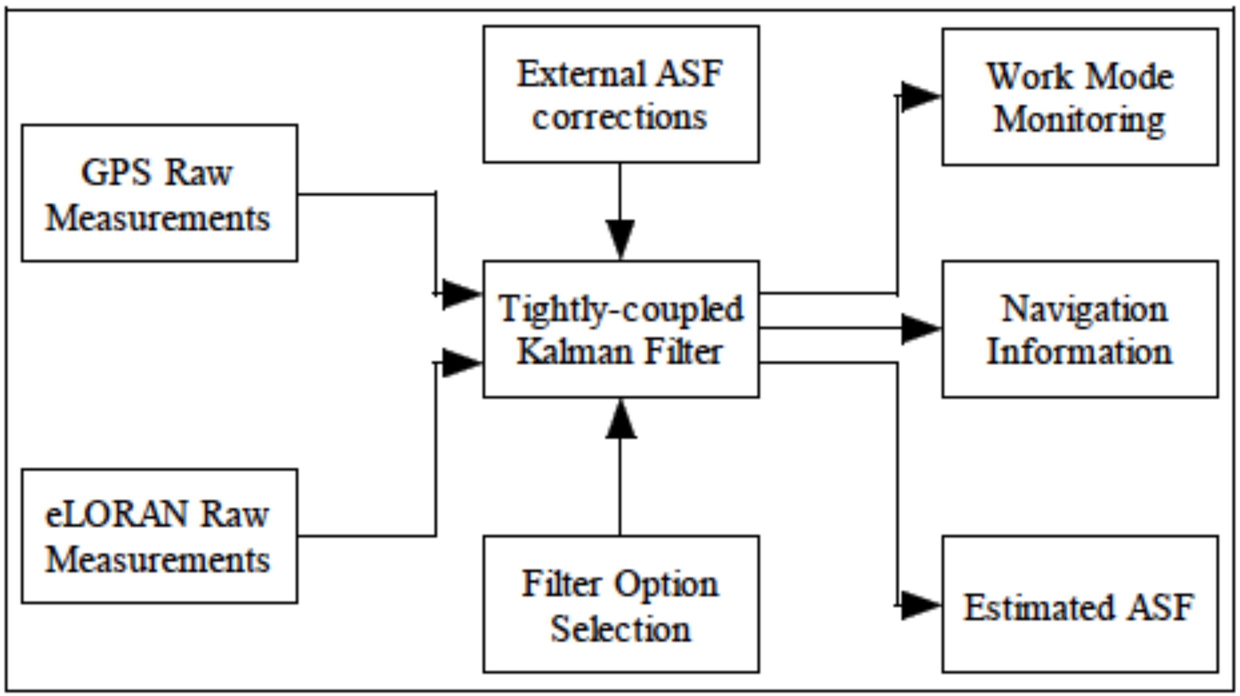


Figure 11: Structure of an integrated GPS/eLORAN system

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

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

GPS Correction

Conclusion: **GPS/GNSS is the backbone of "Assured PNT"** [e.g. Availability, Accuracy, & Integrity]

- Maximize *Synergies* between GPS and Inertial Systems
  - Virtually eliminates Vulnerabilities of GPS/INS to Jamming Threats
  - Eliminates INS initial condition errors and long term error growth
- Emergency Augmentation with eLoran
  - 10/15 Meter Horizontal Accuracy in small calibrated region
  - ¼ to ½ mile accuracy over irregular terrain
  - Two Dimensional (Horizontal) only
  - Not suitable for aircraft – should use DME

PNTAB: Looking Forward

- ***P***rotect the radio spectrum + identify + prosecute interferers
- ***T***oughen GPS receivers against natural and human interference
- ***A***ugment with additional PNT sources and Techniques

- Continue focus on assured PNT: The ***PTA Program***
- Continue Efforts to exploit all ***GNSS*** systems for economic, safety, societal and security value
- New Task: Assessment of the potential user market for a terrestrial-based PNT system; e.g, eLoran.

Thank You

QUESTIONS?

Backups

eLoran Characteristics

Characteristic		eLoran	
		Non-Differential	Differential
System **Availability**		Regional	Local only – e.g. Harbor Area
Accuracy	Horizontal	50m to >500m	10m to 20m
	Vertical	No Vertical (Use Baro?)	
Time to First Fix		1 to 2 Minutes (?)	
Vulnerability to Interference		Nearly Invulnerable	
Cost		$20 + Display& Ant	$20 + Display& Ant

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- **Regional –** But not currently deployed
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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	?