Presentation for ILA 2005

GPS/WAAS/eLoran Airborne Navigator

by

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What is *FreeFlight Systems*

FreeFlight Systems was created in July 2001

- Purchase of Business & Commuter Avionics segment of Trimble Navigation (Austin, TX)
- Key long-term Trimble staff were retained
- Relationship with Trimble continues & is excellent

Trimble

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Objectives

- Show importance of GPS/WAAS to aviation
- *eLoran* as the best backup
- Recent *eLoran* development activity
  - Locus + Rockwell Collins
  - Locus + FreeFlight Systems
  - Deficiencies of equipment relative to aviation
- Summarize current FreeFlight effort
  - Show how effort builds on existing products
  - Preliminary analysis of expected ASF variations
  - *eLoran* project approach & status

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Advantages of GPS

- DoD satellite constellation (24+ satellites) yields navigation available continuously worldwide
- Performance:
  - Accuracy: Position @ 6 m; Velocity @ 0.5 kts (95%)
  - Integrity (protection against HMI)
  - Ground infrastructure & avionics relatively inexpensive
- Suitable as a primary means of navigation
  - Sole means for oceanic & remote operations
  - Applicable to Non-Precision Approach

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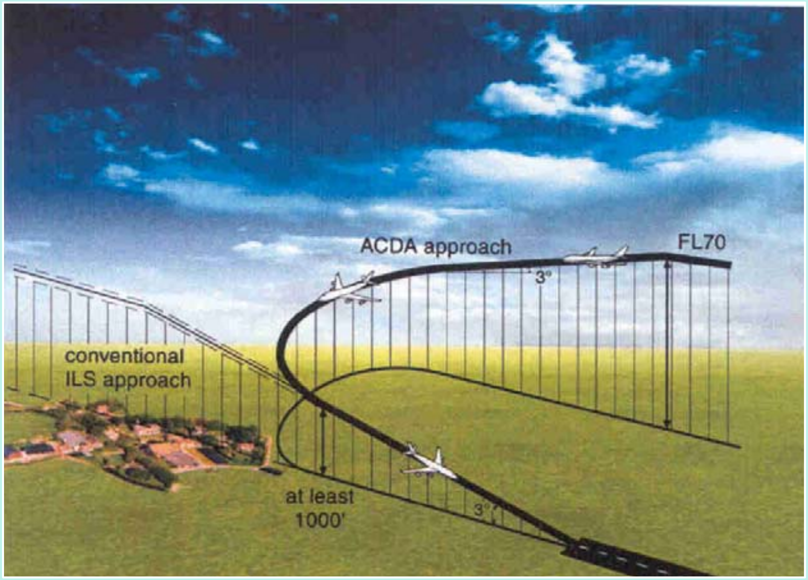
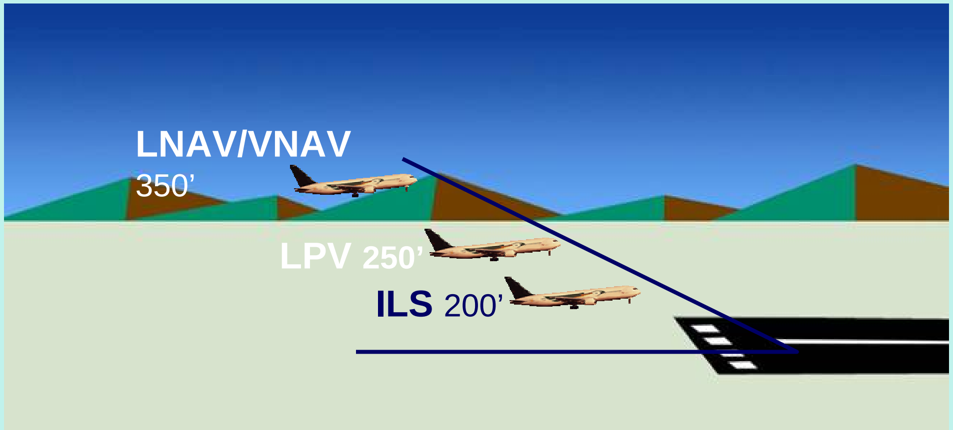
Added Advantages of WAAS

- WAAS = Wide-Area Augmentation System
- Greater accuracy & integrity
- *Precision Approach* capability
  - Back-up for ILS





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Concerns with GPS

- Safety-of-life: Concern with GPS as sole means of navigation
- Satellite-based GPS signals are weak by the time they reach an avionics receiver
- FAA’s entire communication & navigation system is “timed” using GPS.
  - Fixed and cellular communications also depend on GPS *Stratum 1* timing

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eLoran a Cross-Modal Solution

- Though less accurate than GPS, Loran can be applied to:
  - Lateral aircraft navigation: RNP 0.3
  - Harbor entry accuracy for maritime
  - Navigation for ground vehicles
- Stratum 1 timing standard (1/of 3)
  - Only alternatives: GPS & atomic clocks
- WAAS signal on Loran (e.g., Eurofix)

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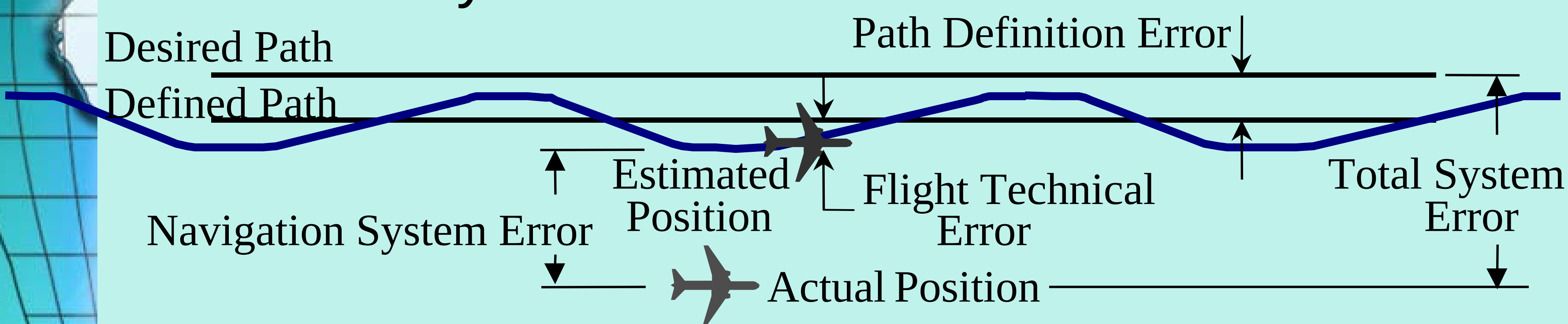
RNP 0.3 Performance for NPA

Performance	RNP 0.3	Loran-C	*eLoran*
Accuracy	307 m	460 m	296 m
Availability	0.9999	0.997	0.999
Integrity	10^{-7}/hr	worse	10^{-7}/hr
Continuity	0.9999	0.997	0.999-9



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Rockwell Collins MMR with Locus *eLoran* Card

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FreeFlight + Locus: Phase 1

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FreeFlight + Locus: Phase 2

Figure : Combined GPS/Loran Navigation unit

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Flight Test Data for Phase 2

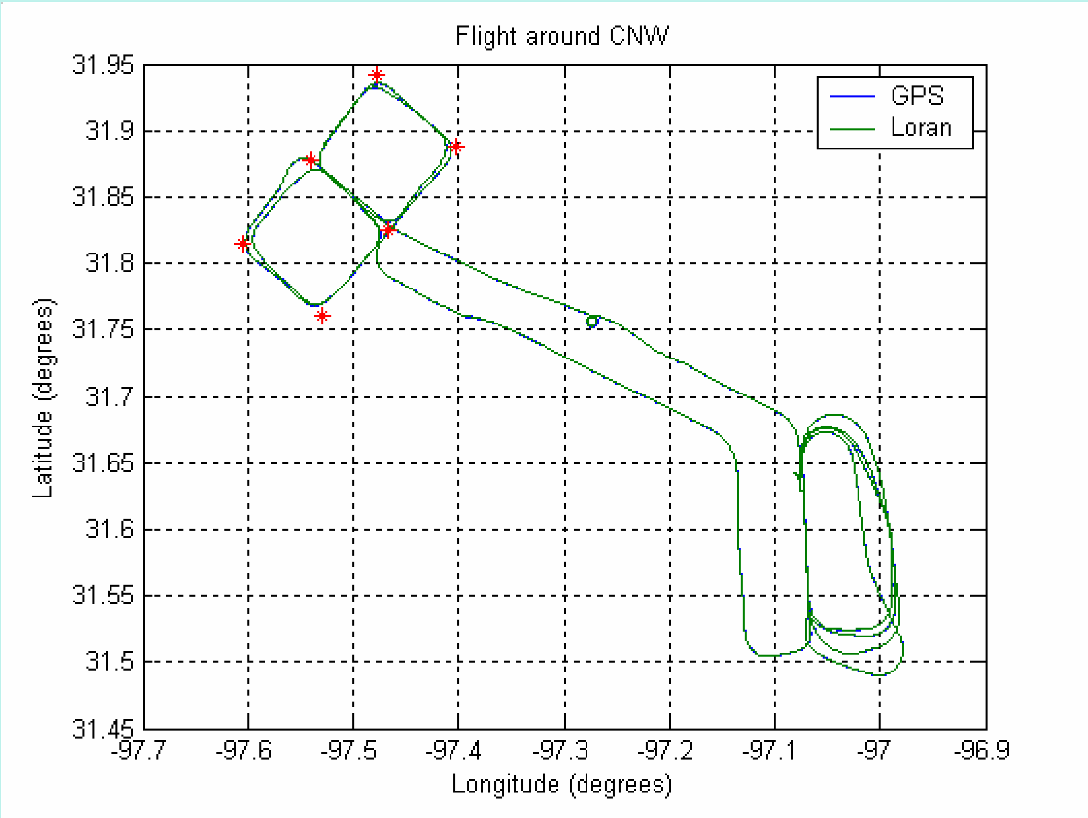

Figure 9: Test flight around Waco, Texas

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GPS/*eLoran* Difference (5 sec filter)

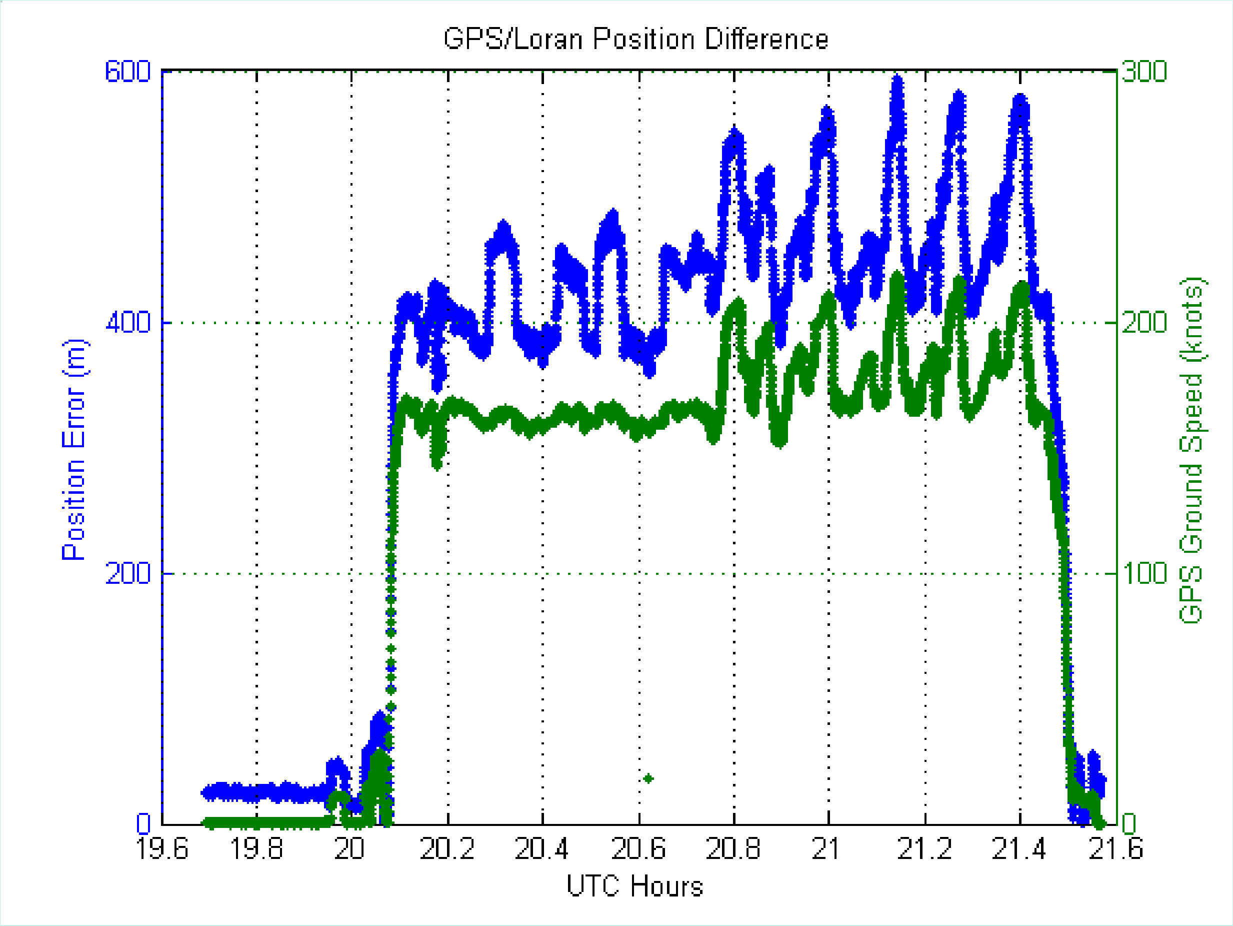

Figure 10: GPS/Loran 2D Position Difference

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In-Track vs. X-track Errors

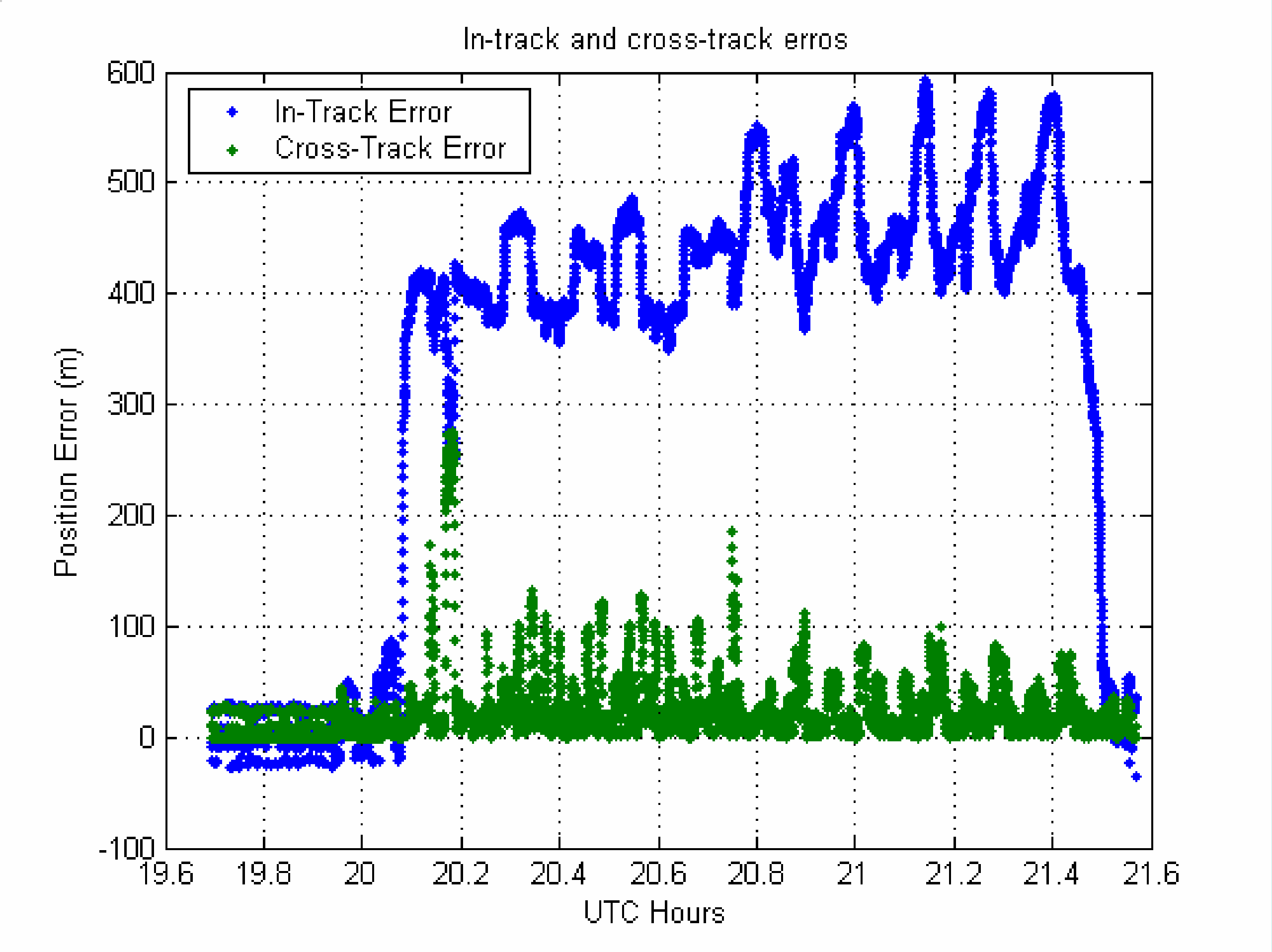

Figure 11: In-track and cross-track error

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GPS/eLoran Difference (corrected)

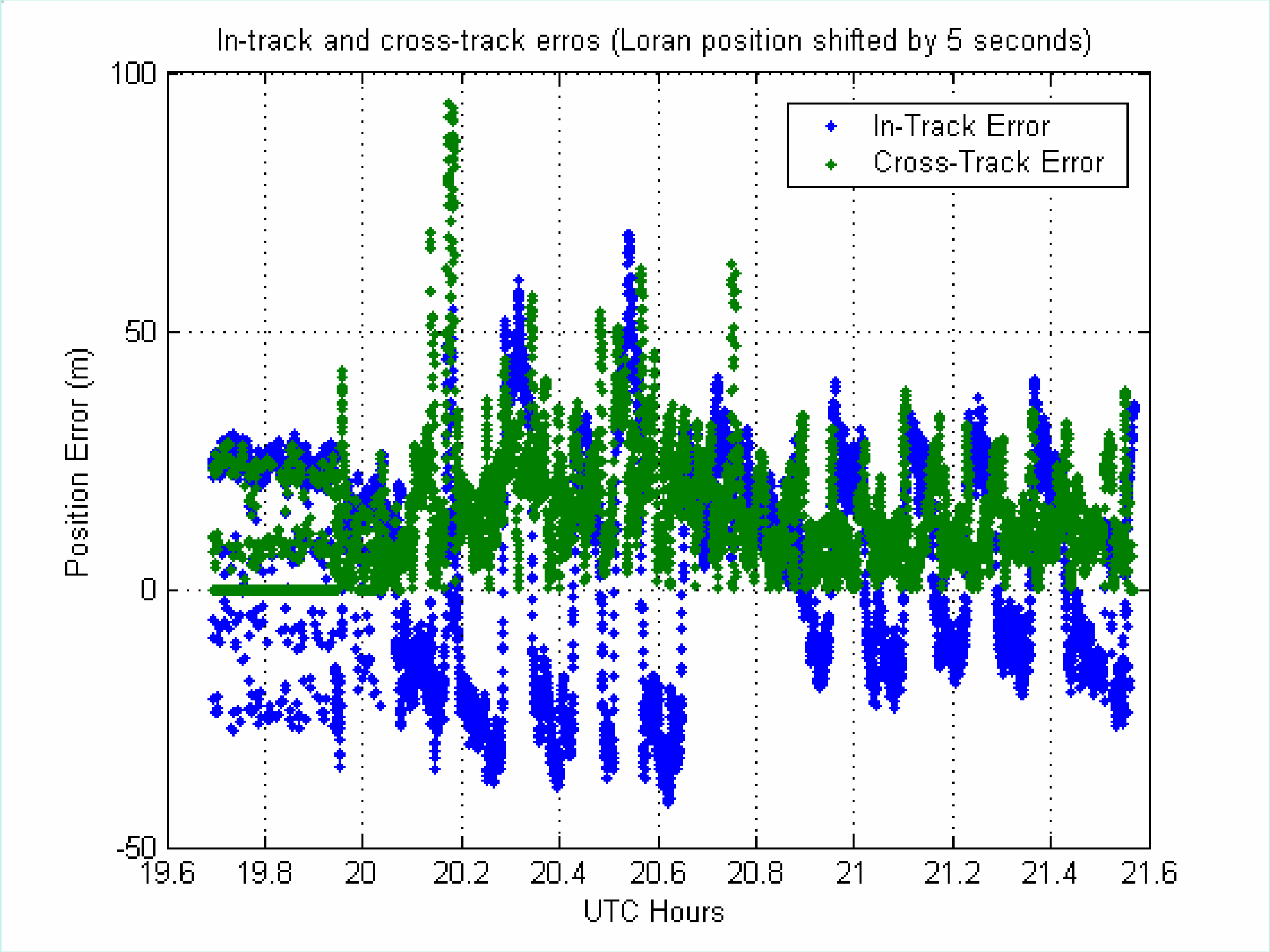

Figure 13: In-track and cross-track errors after 5 second shift

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Role of ASFs in Accuracy

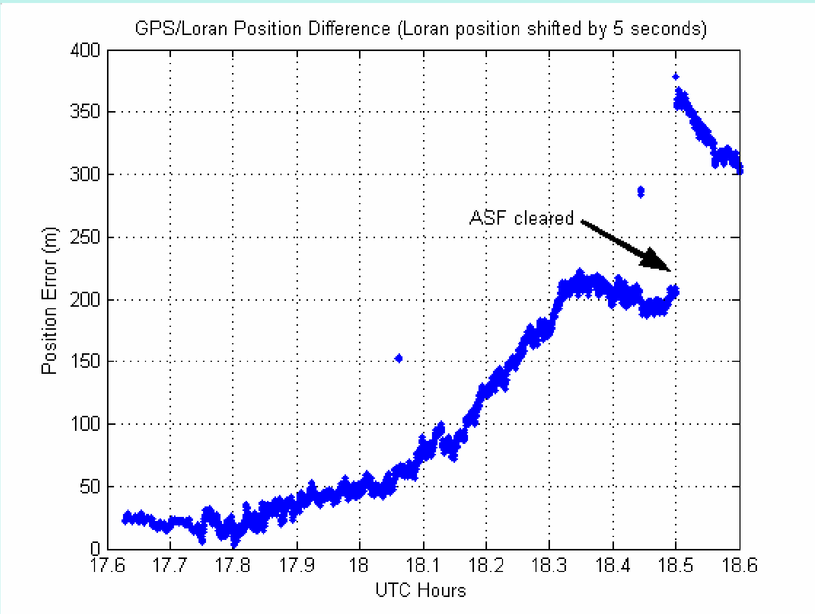

Figure 22: The effect of flying out of the range of ASF applicability

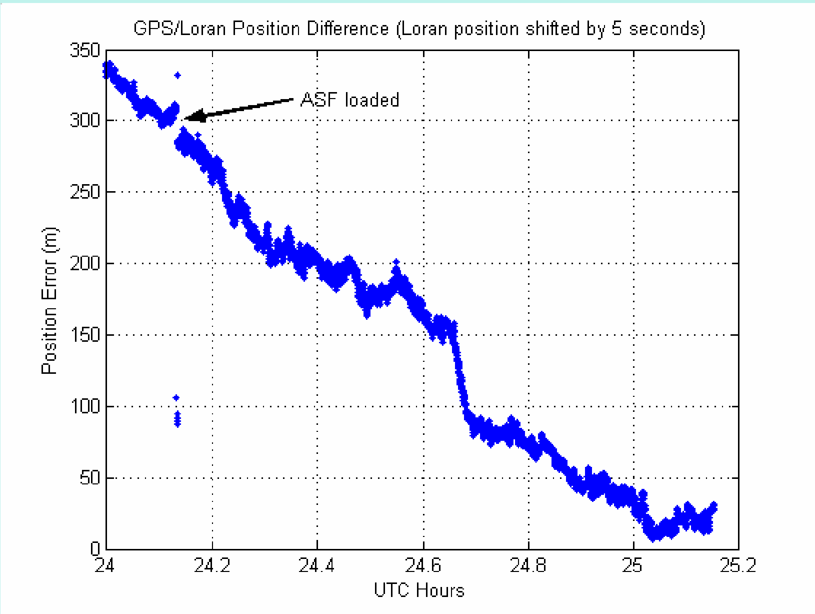

Figure 23: The effect of flying into the range of ASF applicability

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Phase 3: GPS/WAAS + *eLoran*

- Integration of a certifed GPS/WAAS Class Gamma-3 with "non-certified" *eLoran*
  - *eLoran* consultant: Peterson Integrated Geopositioning
  - Kalman Filtering consultants: University of Calgary, Dept. of Geomatics Engineering
    - Profs. M.E. Cannon & G. Lachapelle
    - Sr. Research Assoc: Ning Lu, Ph.D.
- FAA sponsorship – To accelerate development

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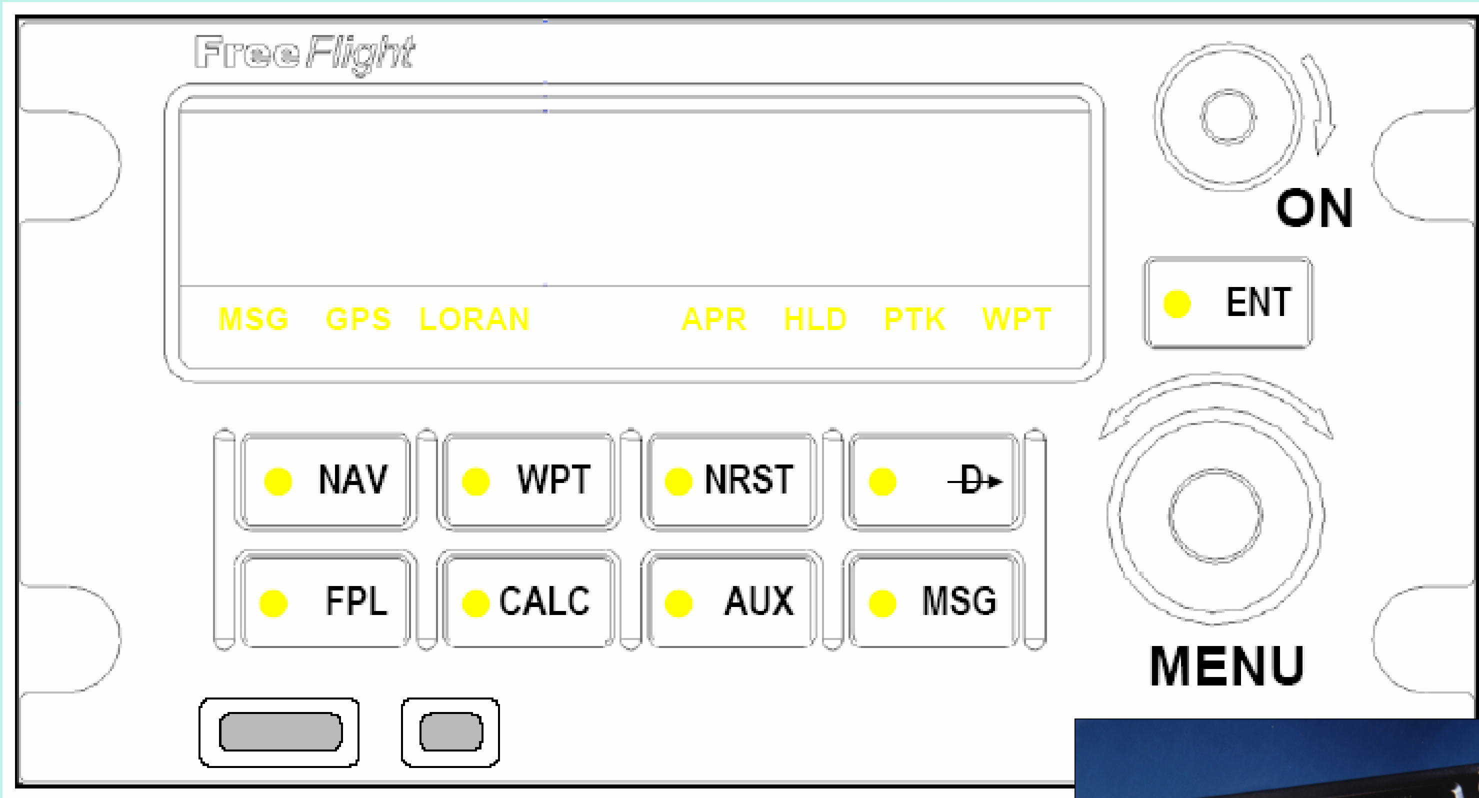
User Interface of Navigator



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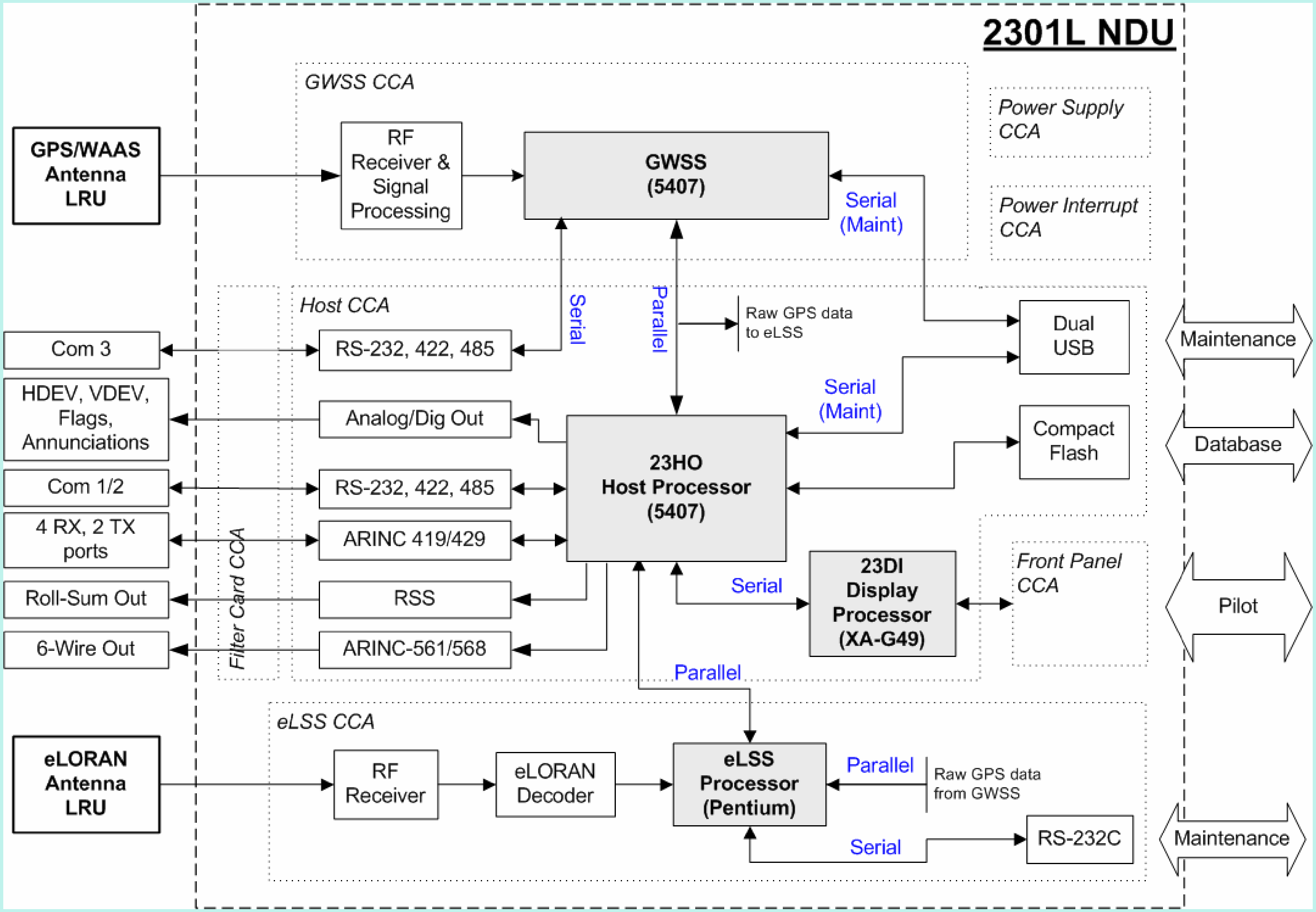
GPS/WAAS/*eLoran* Navigation System



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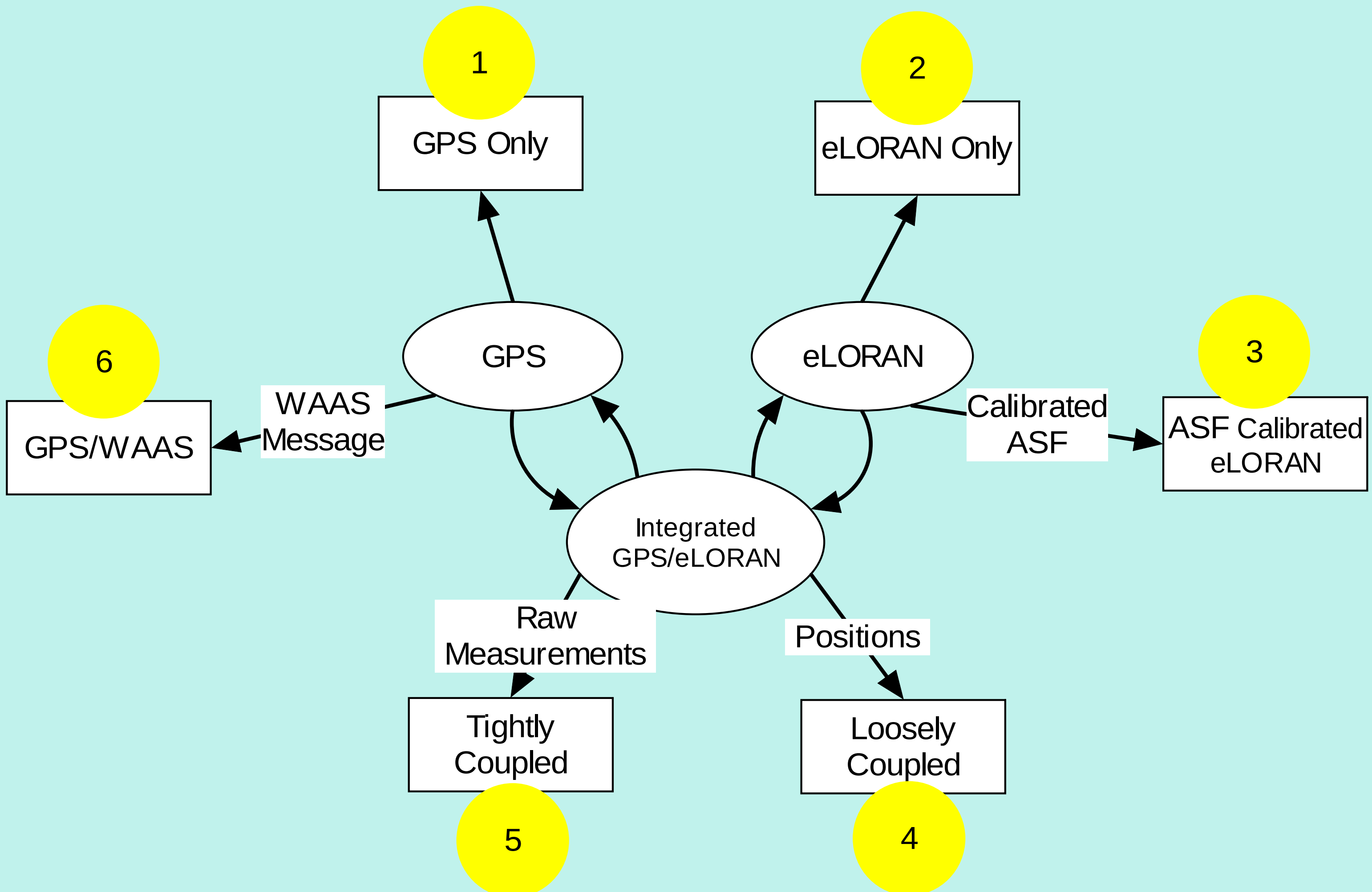
Combinations of GPS/WAAS & *eLoran*



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Options for Tight Coupling

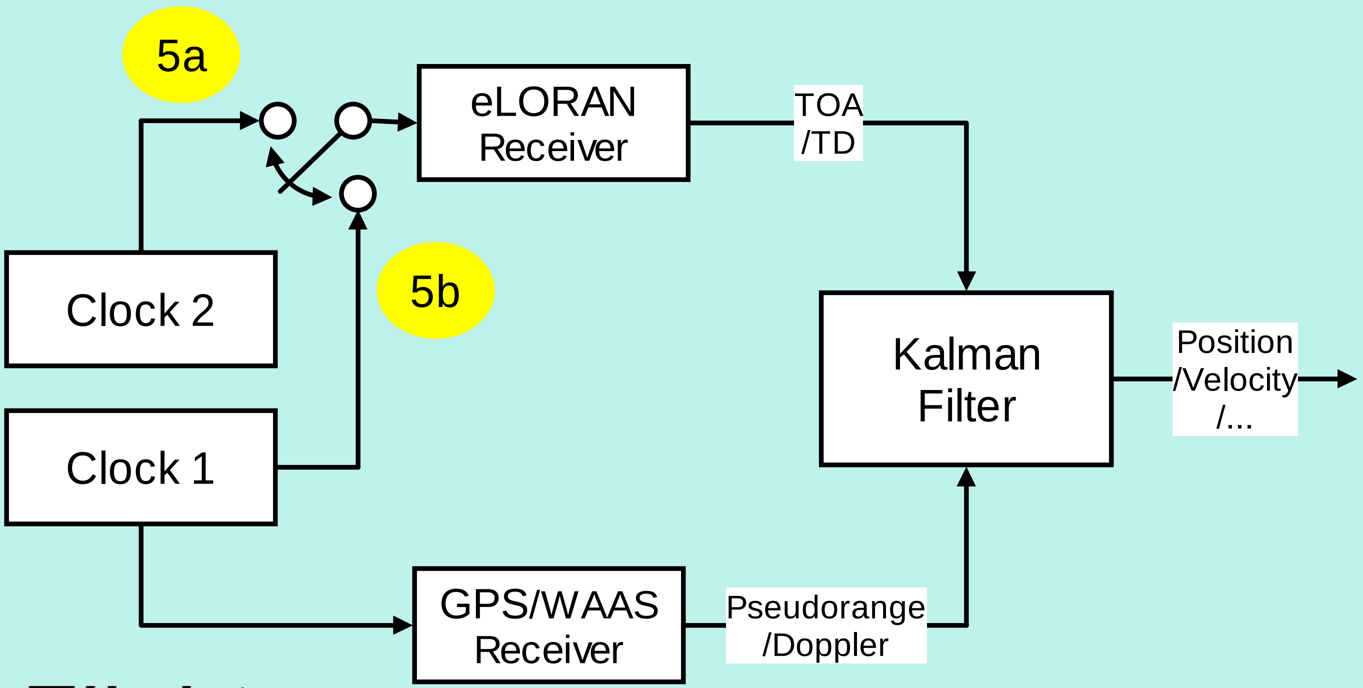
Option 1 (5a)

Two stand-alone units

Option 2 (5b)

Needs both units driven by a common clock

Gain one degree of freedom after filter convergence



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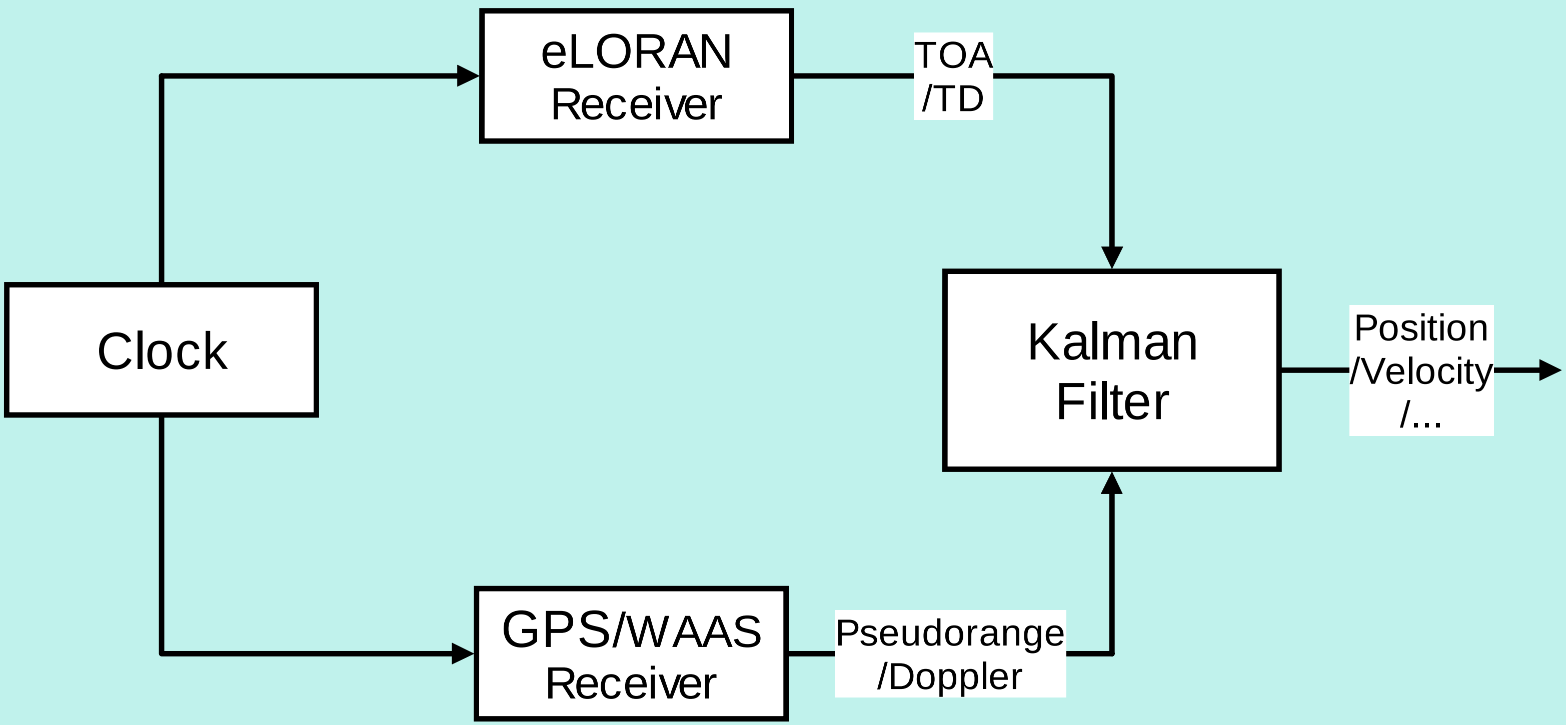
Proposed Implementation



Role of FAA in Producing ASFs

- Current plan: Produce one ASF set of corrections per airport, then validate that a single set meets requirements over the entire approach path and for the entire year.
- If performance deficient:
  - More than one ASF set per airport may be needed, or
  - Real time corrections (as in differential Loran for maritime users) may be needed
    - Strong FAA resistance to this
- In future, FAA may certify multiple airports with a single set of ASF corrections
- Effort underway at University of Calgary to understand variability of ASFs; affects Kalman filter parameters

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ASF Effect Analysis

- TD error analysis – Definition and budget

$$TD_{Err} = TD_{obs} - TD_{Corr}$$

$$TD_{Corr} = TD_{GPS} + PF(d_{GPS}) + SF(d_{GPS})$$

$$= TD_{True} + GPS_{Err} + PF(d) + SF(d) + PF(\Delta d) + SF(\Delta d)$$

$$TD_{Obs} = TD_{True} + PF(d) + SF(d) + ASF + \varepsilon + TX_{Err} + Meas_{Err}$$

$$TD_{Err} = PF(\Delta d) + SF(\Delta d) + ASF + \varepsilon + TX_{Err} + Meas_{Err} + GPS_{Err}$$

Error Type	Error Level	Confidence
GPS (Differential)	12 m	6 sigma
Atmospheric Noise	LORIP Model	6 sigma
Tx Jitter	30 m (TFE control)	6 sigma
Rx Noise	?	6 sigma
Meas Uncertainty	50 m (?)	
PF(Δd)+SF(Δd)	1 m / 500 m position error	

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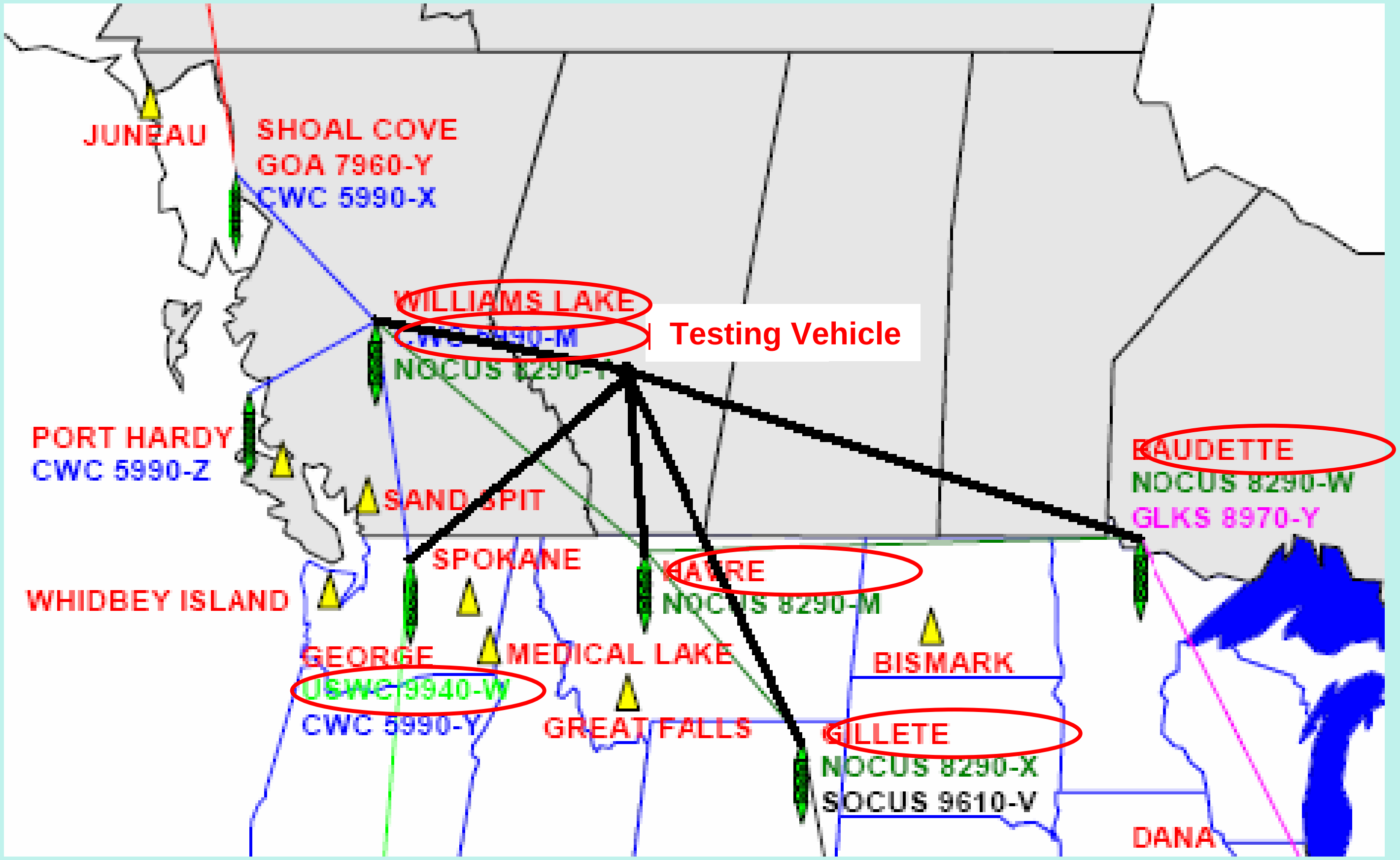
Loran Channels Around Calgary



Canadian West Coast Chain: 5990
North Central U.S. Chain: 8290

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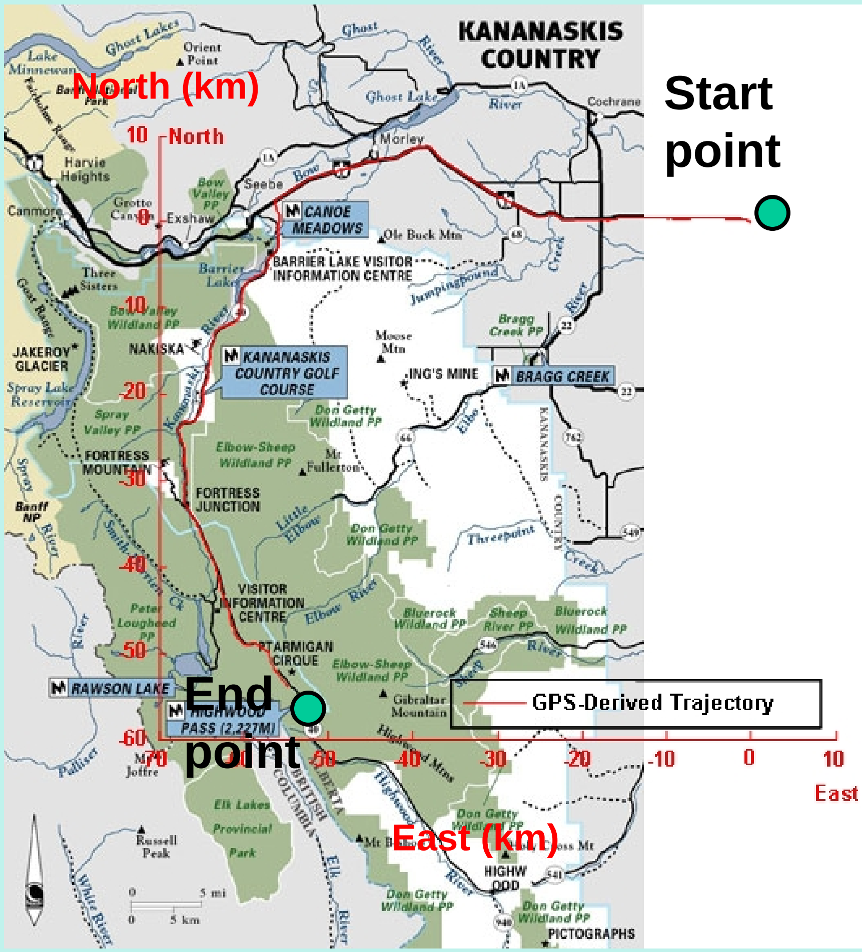
Test Design - Trajectory



- One round trip (255 km)
- Driving at speed limit (80-110 km/h)
- Testing duration : 3.5 hours
- Height variation: 1100 – 2200 m
- GPS receiver used to
  - Generate reference trajectory
  - Time-tag Loran measurements
- Loran receiver:
  - Reelektronika

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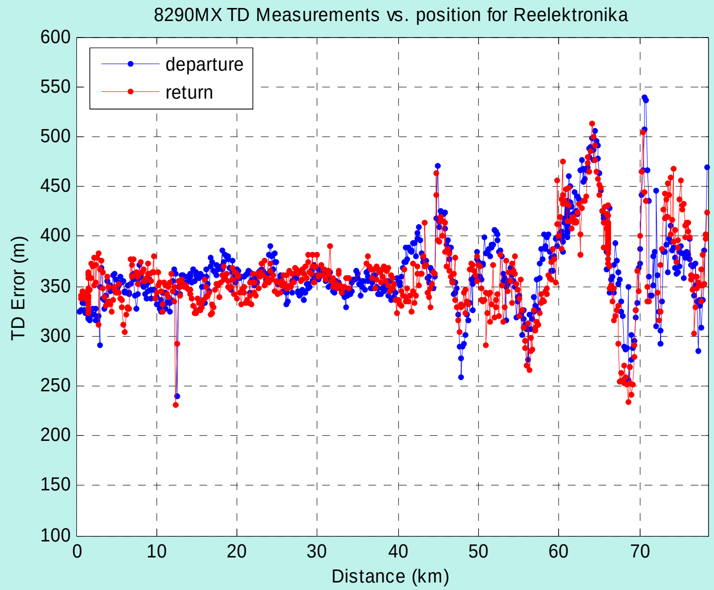
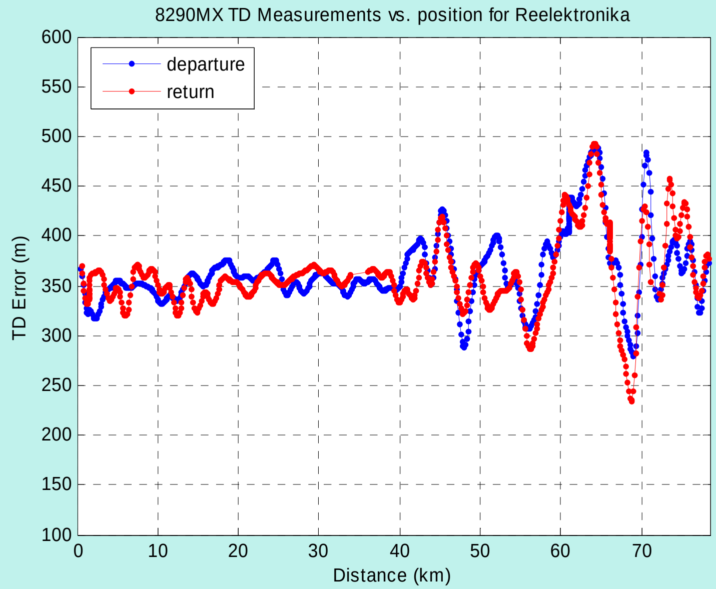
Results: ASF Effects



TD Error (Raw)



TD Error (Filtered)

- Repeatability: Difference between “departure” and return
  - TD Errors + ASF temporal variation (short-term)
  - STD($TD_{departure}$-TD_{return}) = 21 m (incl. ASF temporal contribution)
- ASF spatial variation
  - Max value: 250 m/km (0.83μs/km)

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ASF Handling in Integration Filter

- As measurements (mandatory)
  - ASF corrections provided by external sources (e.g. FAA)
  - Variance bound to cover ASF spatial variations
  - Variance bound to cover ASF temporal variations
- As KF state vector (optional)
  - Stochastic modeling (e.g. 1^{st} order Gauss-Markov process) of ASF spatial variations
  - Use GPS measurements to update ASF estimates (non-Approach only?)
  - Unnecessary to model ASF temporal variations

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User Equipment *eLoran* Requirements (1)

1. H-field antenna to solve p-static problem
2. All-in-view, master-independent receiver
3. Operation in stand-alone mode from power-up
   - *eLoran* must not depend – even partially – on GPS
4. Must store & use FAA-provided ASF data bases
5. Must cancel most Cross-Rate Interference (CRI)
6. Must use non-linear processing to mitigate impulse noise effects

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User Equipment *eLoran* Requirements (2)

7. Must calculate probability of undetected cycle error (~3000 m ranging error!)
8. Must calculate Horizontal Protection Limit (HPL) for comparison with HAL – a function of bias & noise
9. Must demodulate & decode Loran Data Channel (LDC) – 16 possible message types; e.g.,
   – Absolute time & Station ID
   – Early skywave warning
   – Differential Loran (not necessary for aviation)

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Summary & Concluding Remarks

- FAA continues to encourage use of *eLoran* as a back-up to GPS/WAAS for navigation (RNP 0.3) & Stratum 1 precision timing
- FreeFlight Systems is developing a navigator offering GPS/WAAS, eLoran, or a combined, tightly-coupled position solution using a Kalman Filter
- ASF behavior requires further investigation; compatibility with FAA implementation a must
- Program status: CDR planned for 18 Nov 2005
  - Delivery of two units to FAA Tech Center in Aug 06

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