Radionavigation: the only way to go?

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60 Years Radionavigation

- We had Loran-A, Omega, DECCA and Transit, we have GPS, GLONASS and eLoran, and we will get Differential Loran and Galileo
- But people still argue about which one is the best, the most reliable, the cheapest ...
- The US and Europe officially seem to agree on GPS and Galileo? Will Galileo remain civil? Just wait a second!
- Is eLoran civil? The US has reserved room in the 9th pulse message for governmental use?
- Europe, Asia and the US show a remarkable relationship between GNSS and eLoran
  - Are they in a state of cold war, or of warm peace?

Galileo - GPS

EC hints at Galileo military use

Royal Institute of Navigation, Release data 17-Oct-2006

"It is widely reported that Galileo might be opened up for military use – a policy shift that it is suggested would cause a rift between de EC and the UK/US.

According to the Independent, the EC Transport Commissioner has suggested that Galileo might have defence applications. The idea could help to recoup some of the financial outlay on the project, the development costs of which have grown by 500 M€. It would also help to boost to develop a larger military capability to backup its foreign policy – and would be welcomed by France *(the Transport Commissioner is French)"*

System Integration?

- GPS, GLONASS and Galileo
  - Providers: Not really, but improving
  - Users: more and more, pure Galileo receivers unlikely to reach the market
- GNSS and Inertials
  - Aviation: yes
  - Weapons: absolutely!
- GNSS and eLoran
  - Providers: only with Eurofix
  - Users: mainly for DGPS, time, and GPS disciplined ASF fine tuning
  - Deep integration hardly observed

Missed Opportunity

- Formally, we are a large navigation family
- A loving family?
- By many eLoran is at best, but incorrectly, called a **Backup of GPS** interesting for only a relatively small group of high-reliability applications
  - Timing
  - HEA
  - Aviation
- Lack of publicity and public awareness?
  - Hardly possible with Langhorne Bond as president ☺

eLoran Backup Expectations

- eLoran works where GPS can't receive satellites
  - High-sensitivity GPS receivers hard to beat
  - Where GPS can't work, situation for eLoran could also be difficult
    - Reliable non-correlation data available?
- eLoran takes over if GPS is jammed
  - The largest added value of eLoran?
    - Loran jammer not within 10 meters of user

Integration or Selection?

- Deep integration of GPS/eLoran hardly practiced
  - Highest added value today is GPS-calibrated eLoran
- Although eLoran noise performance approaches that of GPS L1, local propagation anomalies makes integration hard job
- Comparing GPS and eLoran range measurements under clean and open-sky conditions, and with zero-mean noise (and interference) give interesting results
- Conditions:
  - no multipath
  - no Loran re-radiation
  - perfect transmitters and ASF models

GPS C/A Code Tracking Noise

$$\tau_N = T_c \sqrt{\frac{B_{loop}}{2} \cdot \frac{N_0}{C} \cdot \frac{d}{T_c}} \cdot 3E8 \text{ meters}$$

τ_N = TOA noise

B_{loop} = tracking loop bandwidth

$\frac{C}{N_0}$ = Carrier-to-Noise ratio

d = correlator spacing

T_c = chip time

GPS Carrier Tracking Noise

$$\tau_N = \frac{1}{\omega} \cdot \sqrt{B_{loop} \cdot \frac{N_0}{C}} \cdot 3E8 \ \text{meters}$$

τ_N = TOA noise

ω = carrier frequency

B_{loop} = tracking loop bandwidth

$\frac{C}{N_0}$ = Carrier-to-Noise ratio

Loran Envelope Tracking Noise

$$\tau_N \approx \frac{10}{\omega} \cdot \sqrt{\frac{B_{loop}}{SNR_i} \cdot \frac{GRI}{8}} \cdot 3E8 \ \text{meters}$$

$\tau_N = \text{TOA noise}$

$\omega = \text{carrier frequency}$

$B_{loop} = \text{tracking loop bandwidth}$

$SNR_i = \text{Signal-to-Noise ratio}$

$GRI = \text{Group Repetition Interval}$

Loran Carrier Tracking Noise

$$\tau_N = \frac{1}{\omega} \cdot \sqrt{\frac{B_{loop}}{SNR_i} \cdot \frac{GRI}{8}} \cdot 3E8 \ \text{meters}$$

τ_N = TOA noise

ω = carrier frequency

B_{loop} = tracking loop bandwidth

SNR_i = Signal-to-Noise ratio

GRI = Group Repetition Interval

Test Conditions

GPS L1

$$f = 1.5\,\text{GHz}$$
$$d = 1\,\mu\text{s}$$
$$T_c = 1\mu\text{s}$$
$$\frac{C}{N_0} = 30\,\text{dB}$$
$$B_{loop} = 1/2\pi\ \text{Hz}$$

eLoran

$$f = 100\,\text{kHz}$$
$$GRI = 0.08\,\text{ms}$$
$$SNR_i = 0\,\text{dB}$$
$$B_{loop} = 1/2\pi\ \text{Hz}$$
$$(\text{rise time} = 1\,\text{s})$$

GPS versus eLoran Tracking Noise

	Carrier	Code/Envelope
GPS	0.16 mm	1.07 m
eLoran	7.6 m	76 m

Ratio = 47,500

Ratio = 7.1

Ratio = 71

- GPS/eLoran carrier ratio = 15,000
- GPS/eLoran modulation frequency ratio = 100
- GPS carrier/modulation ratio = 1,500
- eLoran carrier/modulation ratio = 10

Lowering eLoran Loop Noise

- Integration of data reduces tracking noise
  - 100 times longer integration reduces noise by factor of 10
  - SNR of received signals of -20 dB can be tracked
- Integration requires coherent raw data, so
  - velocity vector shall be constant or known over integration time
  - propagation model shall not change during integration period
  - These requirements shall be met, but how?

Enforce Signal Coherence

- Do not move during integration time
  - Applicable with timing and monitor stations only
- Or, forward external velocity vector variations to tracking loop
  - Maritime & Aviation
    - Course and speed-over-ground
    - No spatial decorrelation of propagation model during integration period
  - Land
    - Odometer and turn-rate
    - Radio compass for absolute heading
    - Propagation model varies strongly in the near field
    - Map matching for normal on-road traffic

Why Worry?

- eLoran in aviation works fine (US)
- HEA performance demonstrated and still further improving (US & UK)
- Station timing excellent (US)
- ASF getting better (US & UK)
- So, count you eLoran blessings ☺

- But, the largest user group is land
- Land is most difficult eLoran application ☹

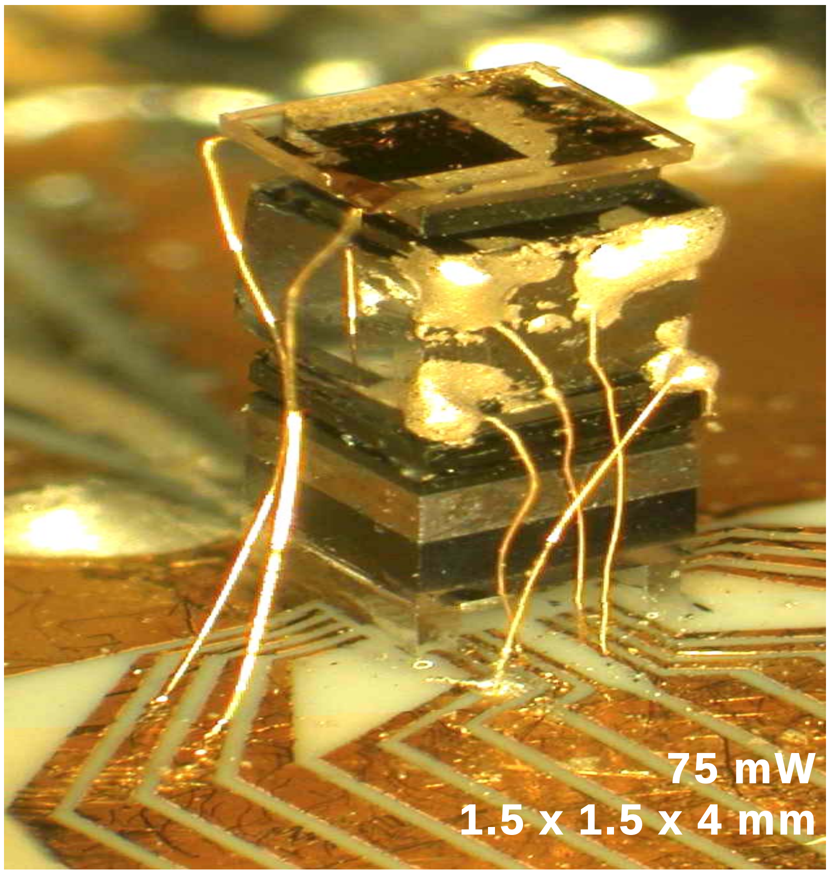
Cars: Ultimate Challenge #1

- High onboard man-made noise levels
  - Ignition, generator, electronics, ...
- Frequent and large near-field propagation anomalies
  - Tall buildings, overhead power lines, ...
- High accuracy wanted at places with poorest signal conditions
  - ¼ Block level needed for street matching
- Car dynamics

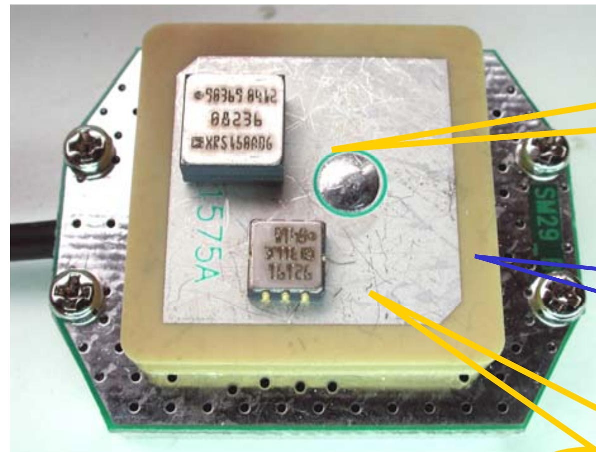
Car Navigation Tools

- Odometer is standard equipment
  - If calibrated, very accurate ☺
- MEMS turn-rate sensors
  - Zero-drift due to temperature variations ☹
  - Non-linear gain ☹
  - Noisy ☹
  - Very low cost ☺
- Map matching
  - Data base most expensive part ☹
  - Extremely robust ☺
  - Excellent tool to calibrate odometer and turn-rate sensor ☺

Clock and MEMS



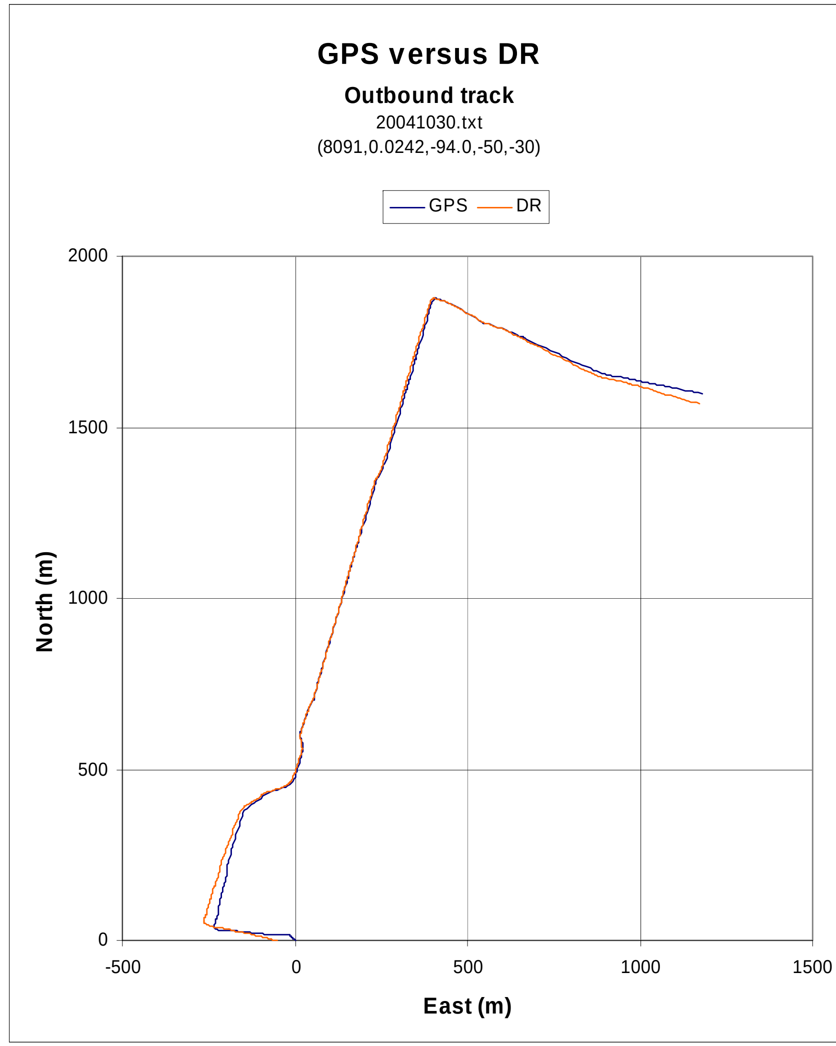
NIST Chip-scale Cs Clock



turn-rate Sensor

50 $ Dead Reckoning

- Standard odometer output
- MEMS turn-rate sensor
- Odometer and turn-rate sensor post-run calibrated
- Test run length 3.2 km
- Accumulated position error < 68 meters



Exploring Renault Carminat

- After initialisation GPS can be switched off for 100 km without getting lost
- After parking GPS is not needed to re-initialise
  - Postion and heading stored in memory
- With GPS on and driving 10 km on unknown roads DR error < 200 m (2%)

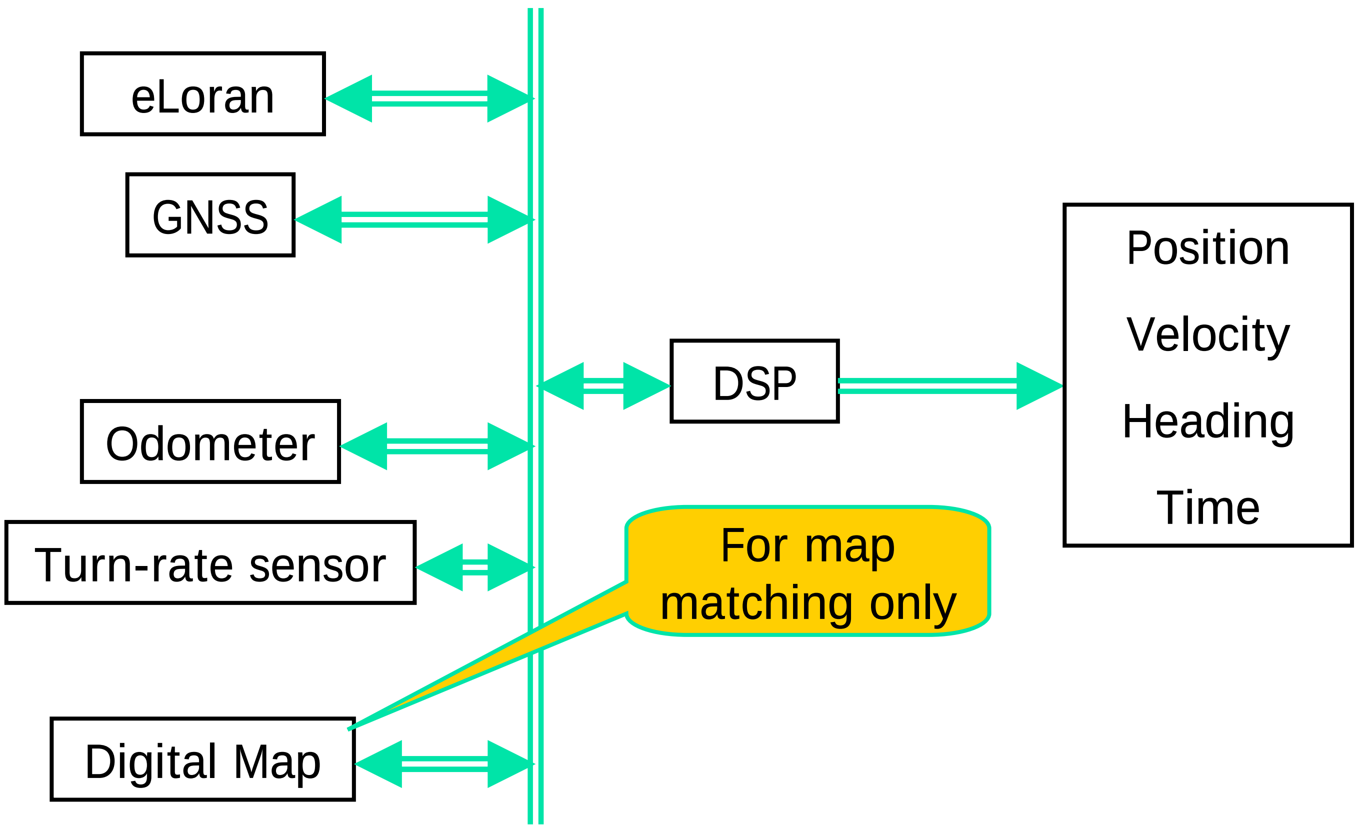
The Verdict on Radio Navigation?

- Odometer **+** turn-rate sensor **+** map matching makes radio navigation superfluous?
  - Mutual calibration makes this a nearly unbeatable team
- Radio position only needed to initialize map-matching process
  - System much ‘know’ where trip starts
  - Last position and heading saved when parked
  - Monitoring

Key Question: RadNav Primary or Secondary?

- Map matching makes e-Nav secondary
- If no map matching available then e-Nav needed for inertial calibration and starting position
- After calibration, e-Nav is secondary again
- E-Nav disciplined inertials challenging and error-prone mechanism
- Excellent e-Nav integrity level is a must to avoid getting lost

Integrated Receiver Concept



Some Calibration Pitfalls

- Calibration should make DR more accurate, not worse
- Requires relative small eLoran position error and very high integrity
- Calibration only allowed when eLoran position is unquestionable
- How to determine eLoran quality in urban canyons or near power lines etc.?

Conditions for Success

- During integration external sensors and propagation model should be more accurate or stable than unaided eLoran
- In open field eLoran TOA noise < 5 m for integration time of 100 seconds
- So, inertial/odometer dead-reckoning should in this 100 sec period not deviate more than 5 meter value

Pedestrians: Ultimate Challenge # 2

- Harsh propagation conditions
- Highest level of accuracy wanted
- Unpredictable pedestrian's dynamics
  - The only prediction is that Vmax < 10 m/s
- Antenna attitude? Any!
- Map-matching won't work as people behave even less disciplined than cars

Approach

- Antenna can be in any attitude
- Calls for 3D antenna, e.g. 3 H-field antennas mutually perpendicular
- Long integration time required to overcome poor SNR
- MEMS sensors needed to counteract dynamic movements of pedestrian
  - 3 turn-rate and 3 linear acceleration sensors needed

Approach, cntd

- Miniaturization requires smallest possible H-field antenna and lowest power consumption
  - Contradiction in terminus
- Can these requirements be solved in a single solution?
- Of course, we definitely have no choice
- Not mentioned for tracking your kid; it is the professional who wants this!

Concluding Questions

- Should we do intertial aiding just to maintain eLoran's primary status operating in poor Loran areas?
- Or, should we go for odometer/turn-rate sensors based dead reckoning and use eLoran for calibrating the inertial sensors?
  - How does the eLoran receiver know its output is of unquestionable quality within a few seconds?

Conclusions

- Major performance leaps made in last decade
- Next large step needed in coming years to attract new user groups
- Integration of Loran, GNSS and shall be intensified
- The Loran part is the most expensive component in an integrated system
  - GNSS receiver including inertials < 50 USD
- The challenges and investments will be major, but the results may be exciting, just like ....

Challenges are Essential Part of Life