On trajectory determination for photogrammetry & remote sensing: sensors, models & exploitation

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AGENDA

1. motivation and introduction
2. **motion sensing & timing**
3. **trajectory error modelling and estimation**
4. **trajectory exploitation**
5. conclusions

… a quick survey on trajectory determination for P&RS

INTRODUCTION

1. trajectory (function of time)

$$\{n(t_0), \ldots, n(t_e)\}, n(t) \in N$$

2. navigation space, examples:

$$N = R^3 \times R^3 \times SO(3)$$

$$N = R^3 \times R^3 \times SO(3) \times R^m$$

$$N = R^3$$

2. orientation / navigation (broad sense of orientation functions)

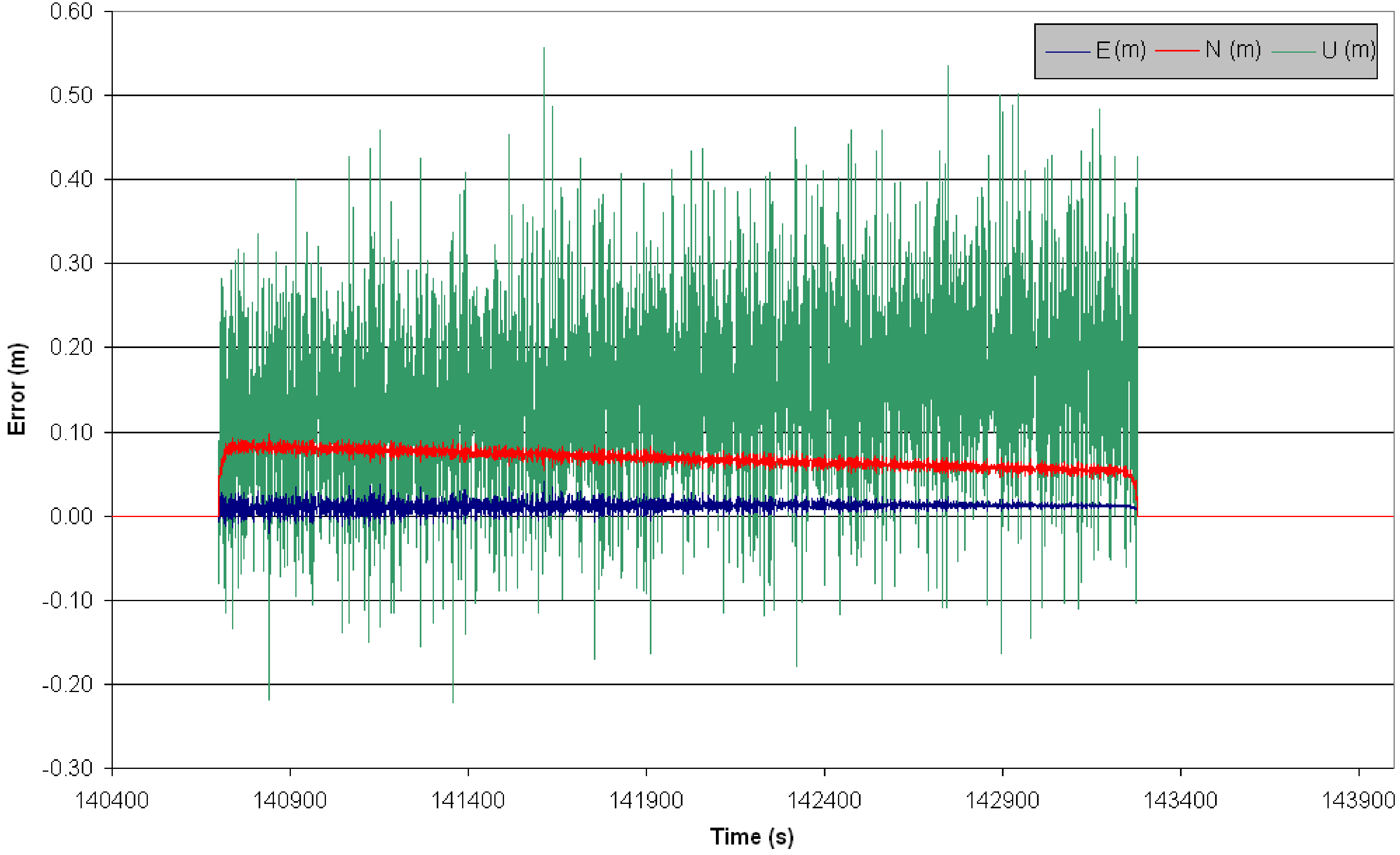
navigation is real-time orientation

MOTION SENSING & TIMING

MOTION SENSING & TIMING

1. GNSS infrastructure
2. inertial sensing & navigation
3. timing

QUESTION: WHAT IS THIS?



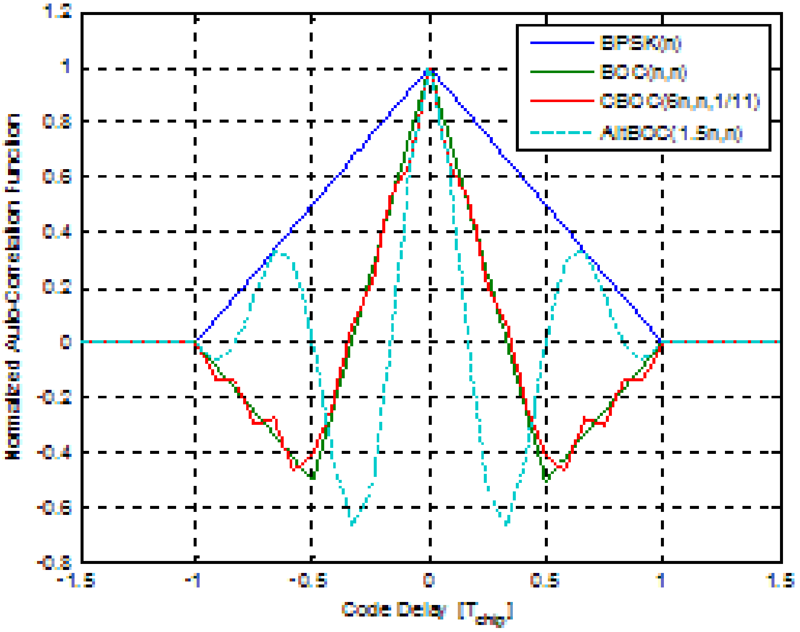
SHORT ANSWER:

the Galileo 2 cm pseudorange
E5 AltBOC revolution !!!

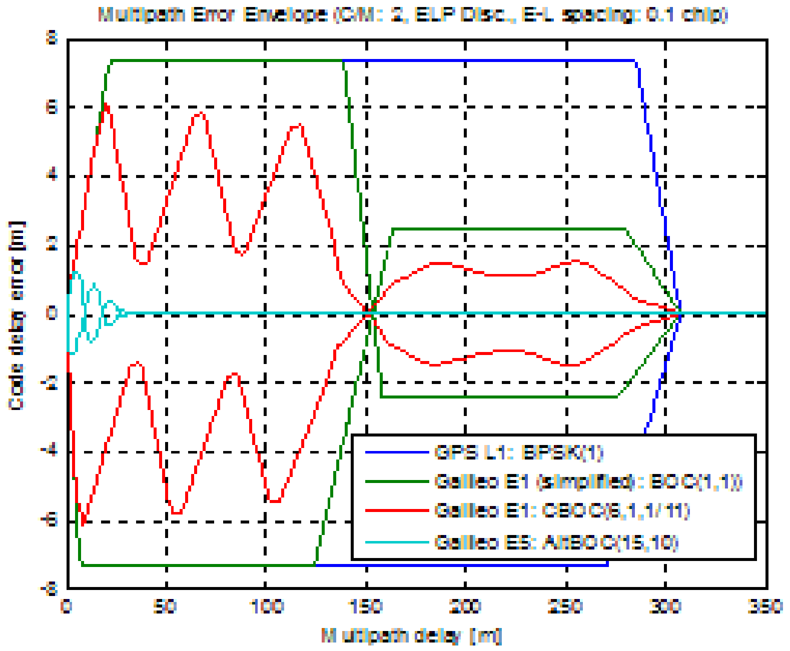
- precise, **accurate** and **robust code** positioning
- **single-frequency** ionospheric determination

ANSWER: Galileo E5 AltBOC (10,15)

AUTO-CORRELATION FUNCTION



MULTIPATH ERROR ENVELOP



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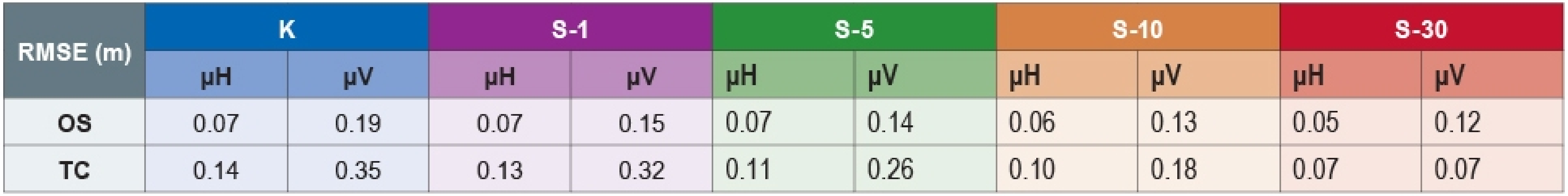
TRACKING ACCURACY AND RANGING PRECISION

		open sky	multipath-fading
E5 AltBOC (15,10)	–	**0.02 m** (44 dB-Hz)	**0.08 m** (40 dB-Hz)
E1 CBOC (6,1,1/11)	–	0.25 m (40 dB-Hz)	2.00 m (36 dB-Hz)

ANSWER: Galileo E5 AltBOC (...) & E1 CBOC (...)



RMSE (m)	K		S-1		S-5		S-10		S-30	
	µH	µV	µH	µV	µH	µV	µH	µV	µH	µV
OS	0.07	0.19	0.07	0.15	0.07	0.14	0.06	0.13	0.05	0.12
TC	0.14	0.35	0.13	0.32	0.11	0.26	0.10	0.18	0.07	0.07

ENCORE PROJECT RESULTS (FP7, GSA)

Colomina,I., Miranda,C., Parés,M.E., Andreotti,M., Hill,C., Silva,P.F., Silva,J.S., Peres,T., Galera Monico, J.F., Camargo,P.O., Fernández,A., Palomo,J., Moreira,J., Streiff,G., Granemann,E.Z., Aguilera, C., 2012. Galileo's surveying potential: E5 pseudorange accuracy. GPS World, Vol. 23, No. 3, march 2012, pp. 18-33.

SINGLE-FREQUENCY IONO-DELAY ESTIMATION WITH Galileo E5 (& BeiDou B2) AltBOC

- 1991-old idea
- group-delay and phase-delay have opposite signs
- of limited practical interest with the original GPS signals
- SX5 project (FP7, GSA): CAC/ANSA 1-2 cm (few min)

Schüler,T., ed. (2012): Precise single-frequency positioning using the Galileo E5 AltBOC signal. Results from project "SX5 – Scientific Service Support Based on Galileo E5 Receivers." Memorandum No. 2, Universität der Bundeswehr München, pp. 217.

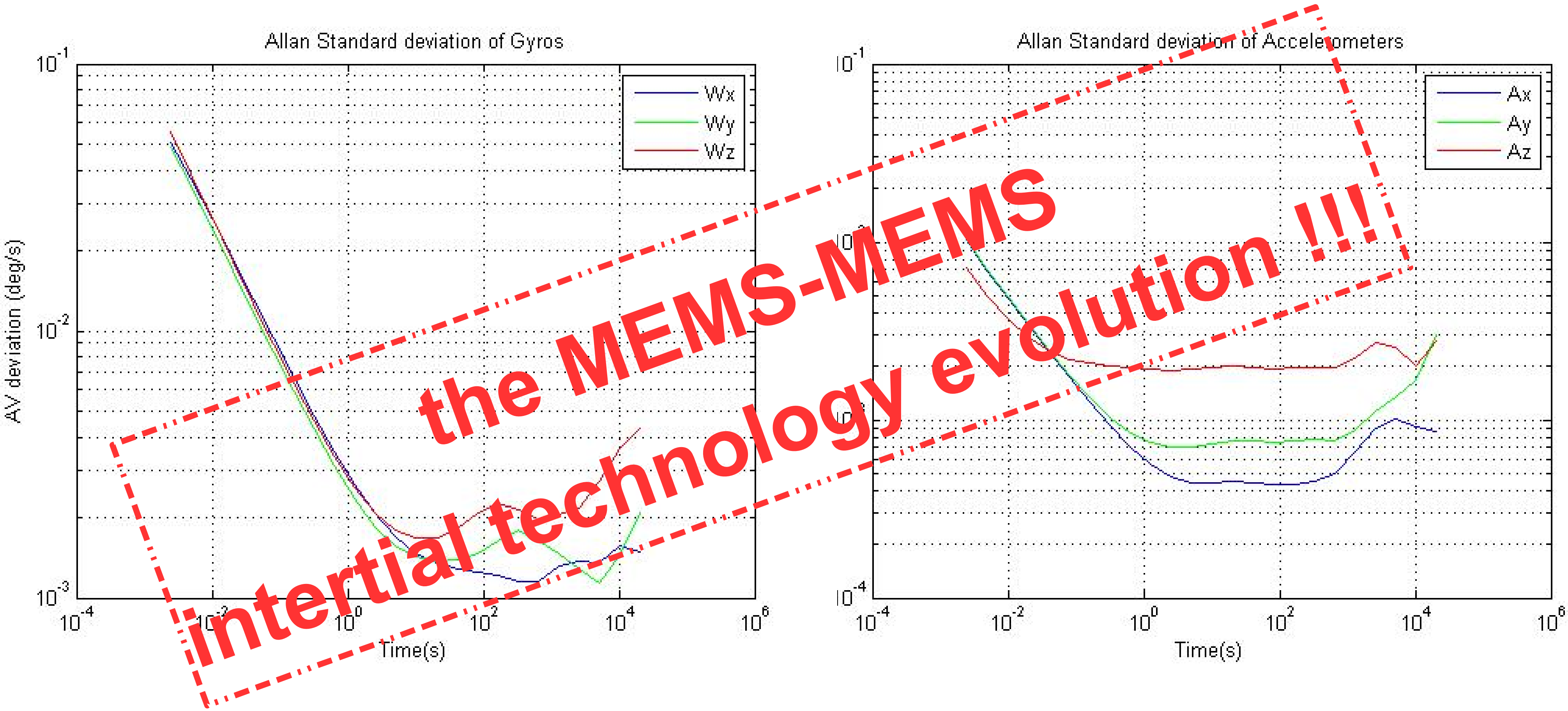
GNSS INFRASTRUCTURE BY 2020

- GPS (32), GLONASS (29), BeiDou (30+5) & Galileo (30)
- 30 - 40 satellites in-view at any time
- 12 signals
- ≈ 1000 channel receivers
- **IGS products (GPS)**
  - orbits: 2.5 cm (1D, RMS)
  - clocks: 75 ps (RMS) – 75 x 10^{-12} s – 2.25 cm

QUESTION: WHAT IS THIS?

volume	2.4 x 2.4 x 1 cm^3
weight	7 g
power consumption	99 mW
in-run / run-to-run bias	3 / 1800 deg/h
in-run	< 0.01 m/s^2
cost	2 k€

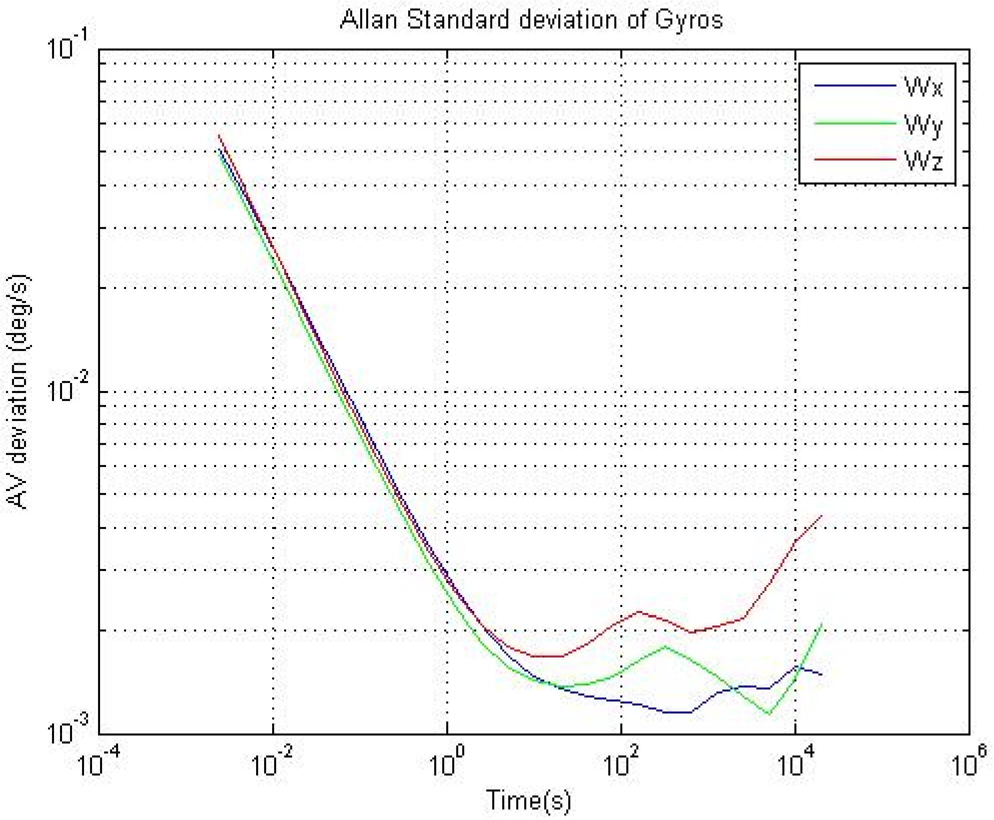
SHORT ANSWER

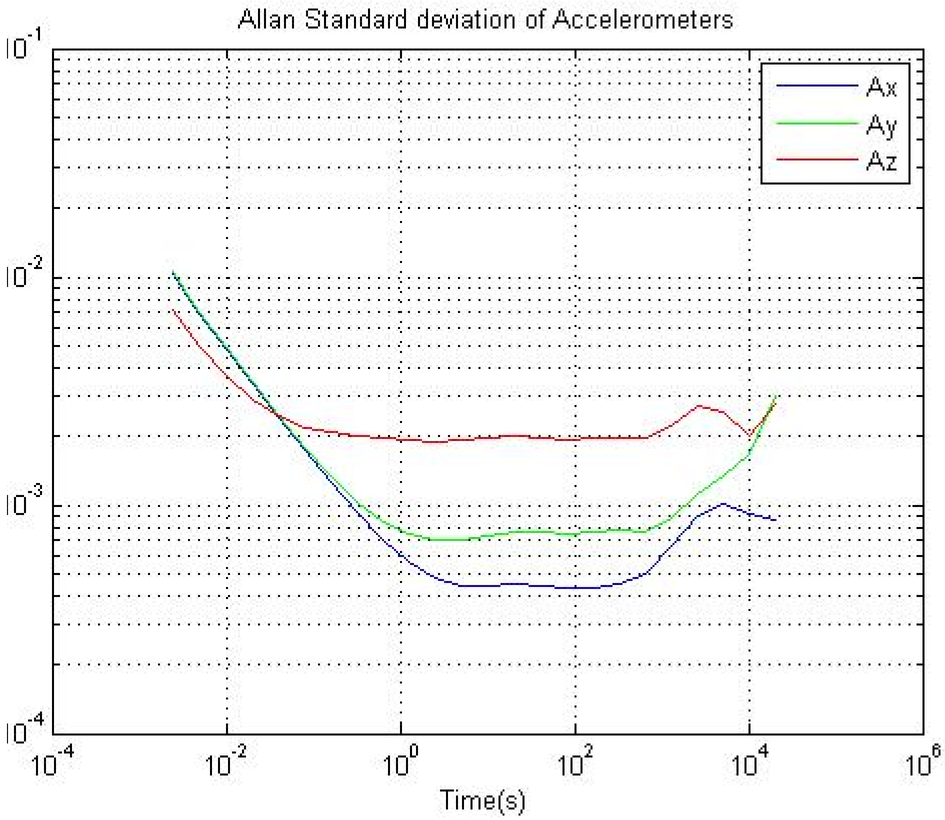


the MEMS-MEMS intertial technology evolution !!!

AV plots courtesy of CTTC.

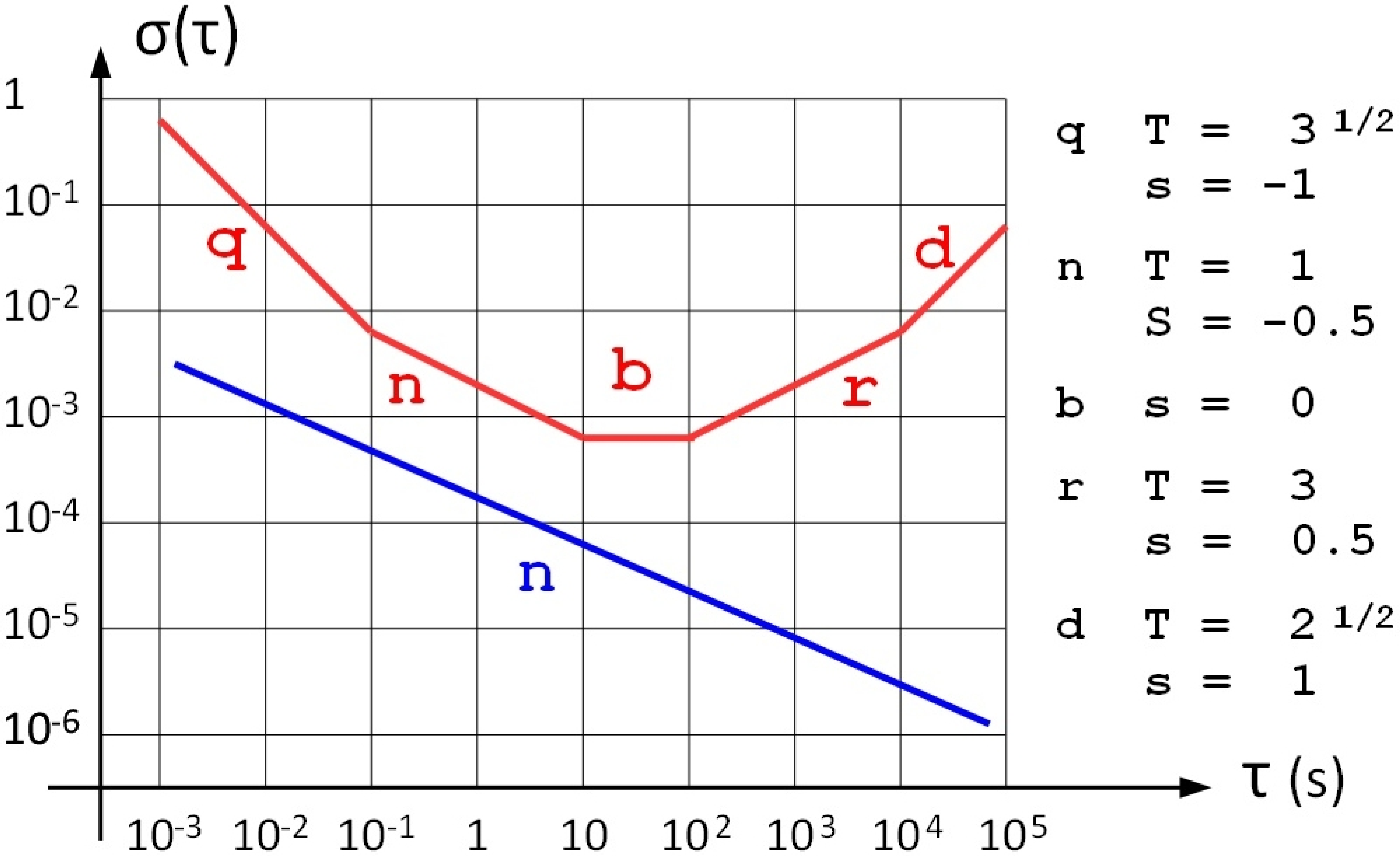
PROPER ANSWER: THE EPSON M-G363/350 IMU





AV plots courtesy of CTTC.

SQUARE ROOT OF ALLAN VARIANCE



q T = $3^{1/2}$
s = -1

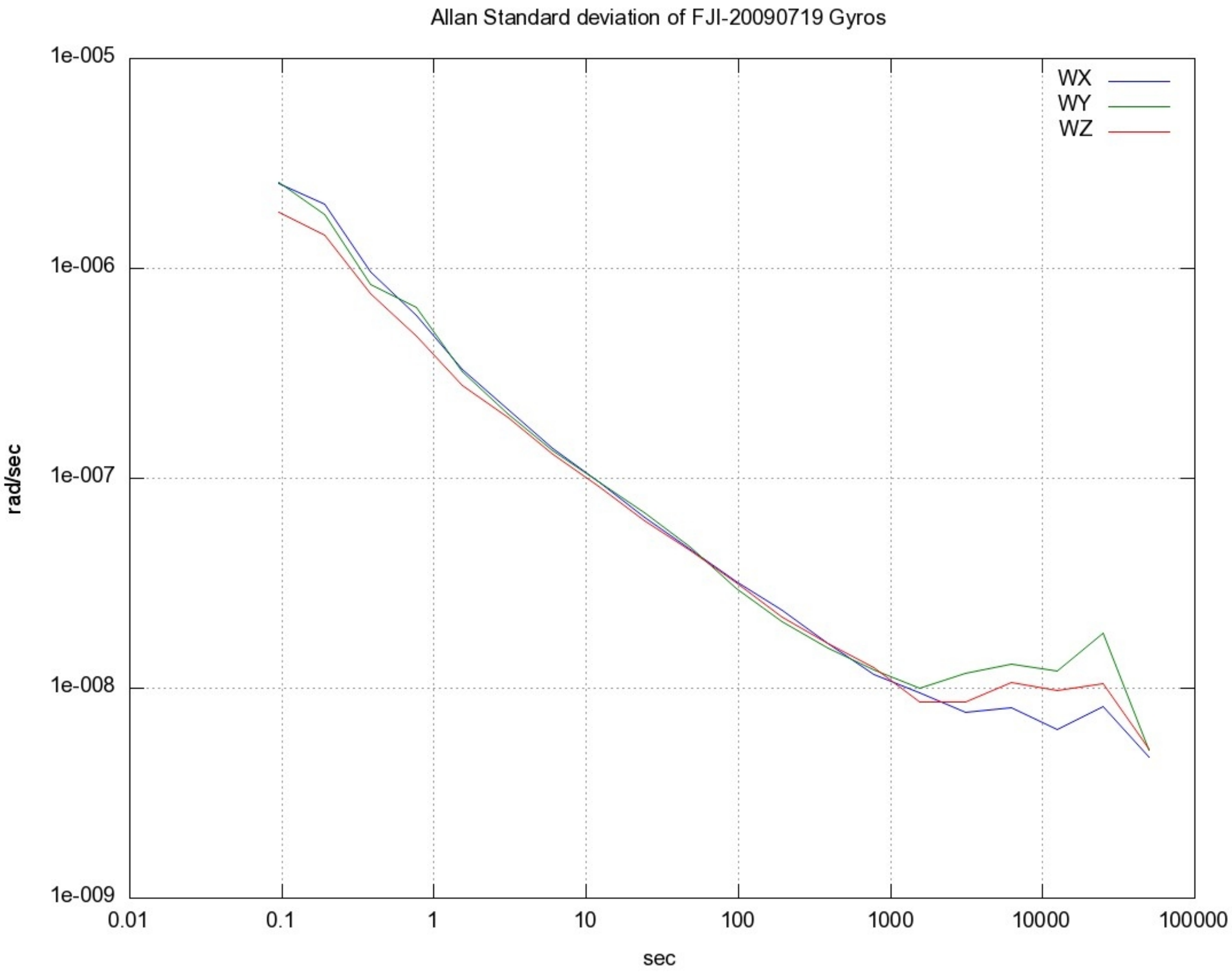
n T = 1
S = -0.5

b s = 0

r T = 3
s = 0.5

d T = $2^{1/2}$
s = 1

NICE 2 km-COIL FOG @ 130 k€ / IMU



AV plots courtesy of CTTC

COMPARATIVE NOISE FIGURES FROM AV

IMU	w (deg/h)	A (m/s^2)	k€
iMAR FJI	0.10	0.00001	130
Honeywell CIMU	1.00	0.00025	60
Honeywell HG1700	2.00	0.00025	20
NavChip	6.00	0.00050	2
EPSON M-G350	12.00	0.00060	2
Maxim MAX21100	36.00	0.00320	0.003

MEMS-MEMS / PP / P: 0.02-0.05 m V: 0.01-0.02 m/s A: 0.03-0.10 deg

QUESTION: WHAT IS THIS?

volume	4 x 3.5 x 1.1 cm^3
weight	35 g
power consumption	120 mW
stability (Allan Variance)	8×10^{-12} (over 1000 s interval)
MTBF	> 100000 h
cost	2 k€

SHORT ANSWER:

the revolution of low-cost precision portable timekeeping !

- 1 µs over 24 h time interval
- GPS-timing equivalent over 1 h

ANSWER: A CHIP-SCALE ATOMIC CLOK

- It can bridge GPS timing gaps for about 3000 s
  - guarantees multi-sensor synchronization (e.g., radar)
- It can detect jamming and spoofing
- It “reduces” the number of essential unknowns from 4 to 3
- In GNSS positioning: correlated height & time unknowns
  - improvement of up to 60% in the height component

Krawinkel,T.,Schön,S., 2014. Applying Miniaturized Atomic Clocks for Improved Kinematic GNSS Single Point Positioning. In: Proceedings of the 27th Internaational Technical Meeting of the ION Satellite Division, ION GNSS 2014, Tampa, Florida, USA.

ERROR MODELLING & ESTIMATION

ERROR MODELLING & ESTIMATION

1. trajectory-level error models
2. sensor-level error models
3. relative & absolute error models
4. navigation and geodetic approaches to estimation

TRAJECTORY-LEVEL ERROR MODELS

- model the results of the errors, not the sources
- in principle, less sound/effective than sensor-error models
- old, good friends of us (GPS-shifts of GPS AT)
- easy to implement in software
- recently being used in terrestrial mobile mapping systems

  step 2 of two-step INS/GNSS + inverse imaging
- most times deterministic
  - piecewise C^n polynomials, ...

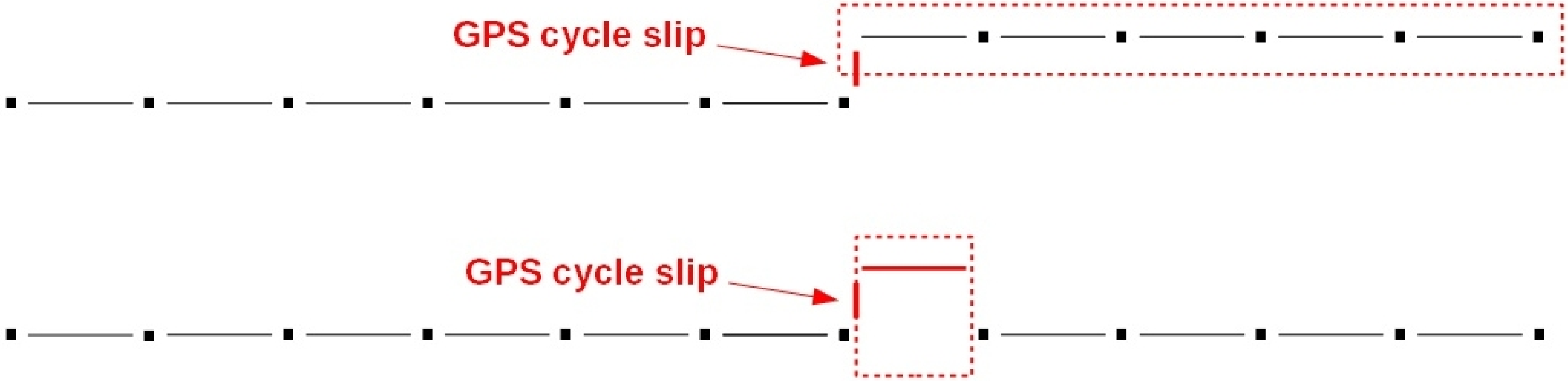
SENSOR-LEVEL ERROR MODELS

- model the error sources
- in principle, the optimal strategy
- old stubborn friends (don't let themselves be modelled easily)
- usually being used in one-step INS/GNSS/… integration

  … but not in step 2 of two-step INS/GNSS + inverse imaging
- most times stochastic
  - random walk, 1st order Gauss-Markov

ABSOLUTE & RELATIVE ERROR MODELS

1. tPA absolute error models do not allow to approach the correlated nature of trajectory errors (and of outlier effects).
2. tPA relative error models closer reflect actual errors; e.g. a GPS cycle slip.



Blázquez,M., Colomina,I., 2012. Relative INS/GNSS aerial control in integrated sensor orientation: models and performance. ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 67, No. 1, pp. 120-133.

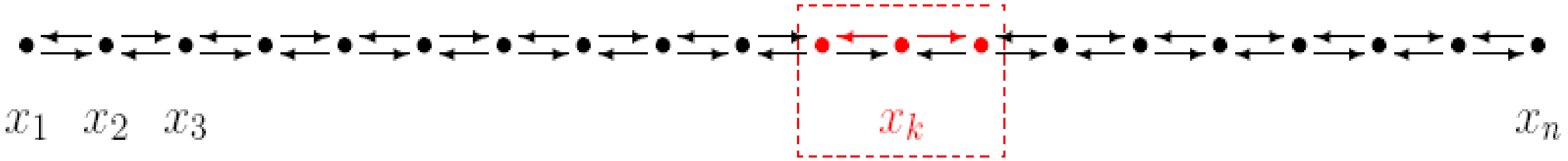
NAVIGATION “vs” GEODETIC ESTIMATION

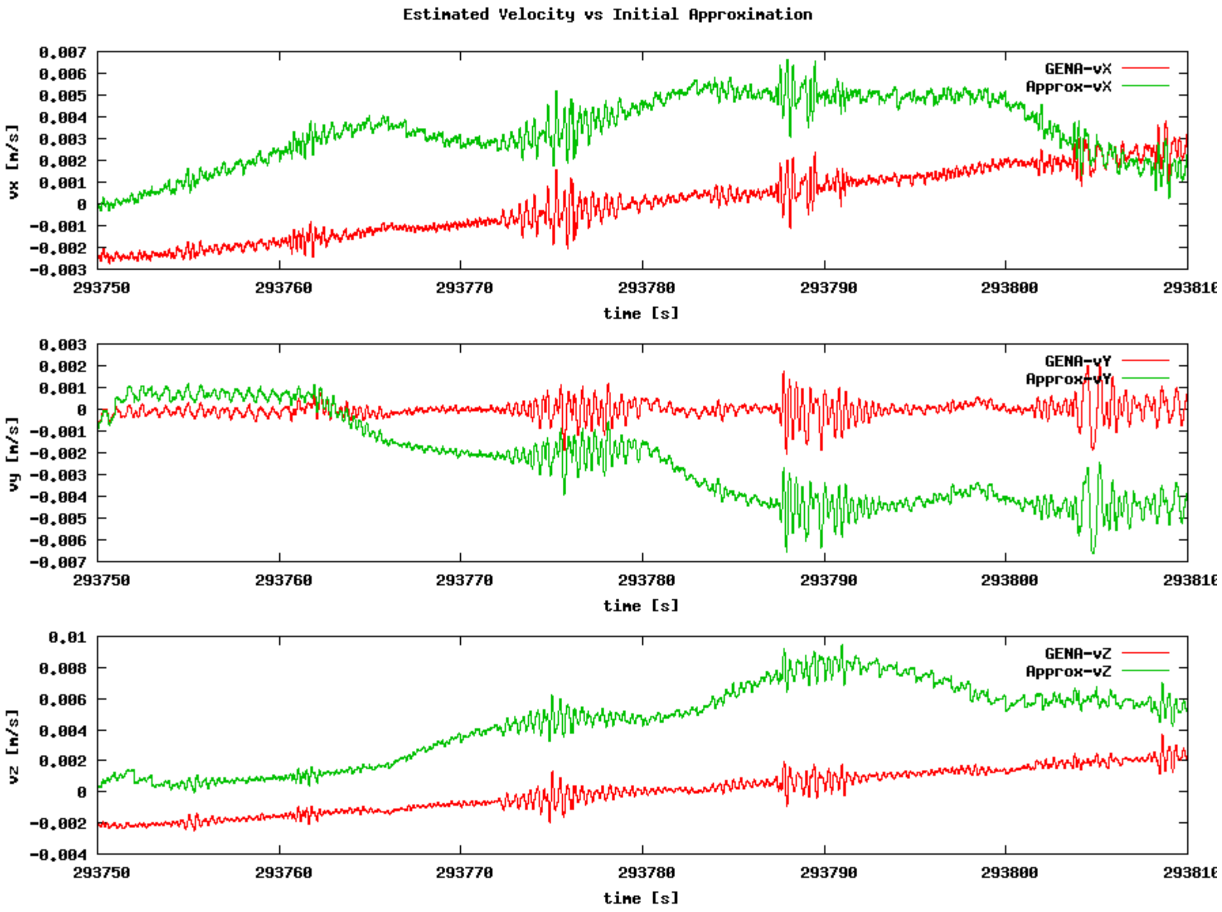
INS/GNSS/… **applications** for trajectory estimation

- **navigation**: always a **real-time** task
  - estimation: predictive filtering (PF)
    sequential least-squares with SE and SDE
    or more sophisticated like UKF or PF
- **orientation**: usually a **post-mission** task
  - estimation: PF, **why? Is there any geodetic approach?**
    … 2004-old idea of dynamic networks

dynamic networks:
approximate the derivatives of an SDE by finite differences.

NAVIGATION & GEODETIC ESTIMATION





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velocity improvement

cross-overs

dynamic networks

vs

KFS

TRAJECTORY EXPLOITATION

TRAJECTORY EXPLOITATION

1. the contents of INS/GNSS-derived trajectories

2. 4D spatiotemporal calibration

3. simplification of image matching (FAST AT)

CONTENTS OF INS/GNSS-TRAJECTORIES

- an image 12-orientation parameters (P, V, A, Ω)

$$s_c^l = (p^l, v^l, \gamma_c^l, \omega_{lc}^c)$$

$$o_c^l = (p^l, \quad \gamma_c^l \quad)$$

$$\dot{p}^l = v^l, \quad \dot{R}(\gamma)_c^l = R(\gamma)_c^l \Omega(\omega)_{lc}^c.$$

- (P, V, A, Ω) have a well-defined mathematical structure
- applications to 4D spacetime calibration, image deblurring or modelling of focal-plane shutter effects

Colomina,I., Blázquez,M., 2014. Pose versus state: are sensor position and attitude sufficient for modern photogrammetry and remote sensing. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XL-3/W1, pp. 33-37, EuroCOW 2014.

4D SPACETIME SENSOR/SYSTEM CALIBRATION

1. positioning / timing use to be non-separable: e.g., GPS positioning
2. orientation / calibration not an exception; e.g., sync. errors
3. 1 ms time-error determination is achievable using

$$s_c^l = (p^l, v^l, \gamma_c^l, \omega_{lc}^c)$$

and appropriate spacetime orientation-calibration models

Blázquez,M.,Colomina,I., 2012. On INS/GNSS-based time synchronization in photogrammetric and remote sensing multi-sensor systems. PFG Photogrammetrie, Fernerkundung, Geoinformation, Vol. 2012, No. 2, pp. 91 104.

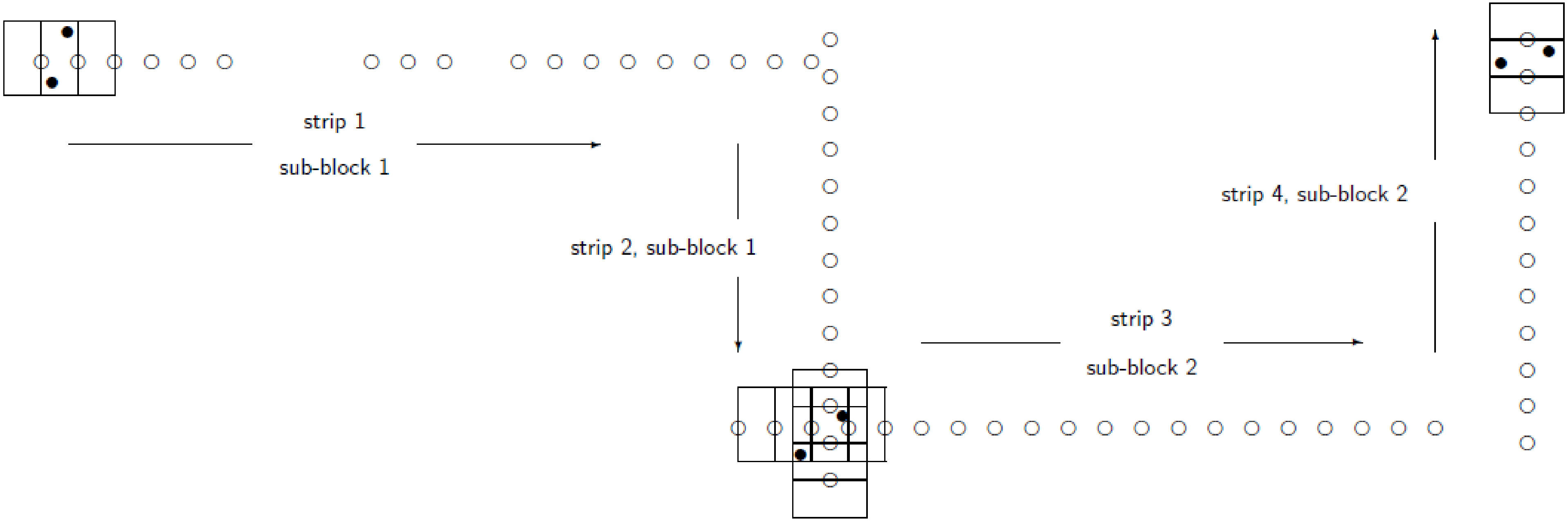
AT WITH LESS IMAGE MATCHING

a quality trajectory can be used for

- direct sensor orientation (DiSO)
- integrated sensor orientation (ISO)
- also for bridging non-overlapping images or reduce image processing

Blázquez,M.,Colomina,I., 2012. Fast AT: a simple procedure for quasi direct orientation. ISPRS Journal of Photogrammetry and Remote Sensing Vol. 71, No. 1, pp. 1-11.

FAST AT: MAXIMAL SIMPLIFICATION / BRIDGING



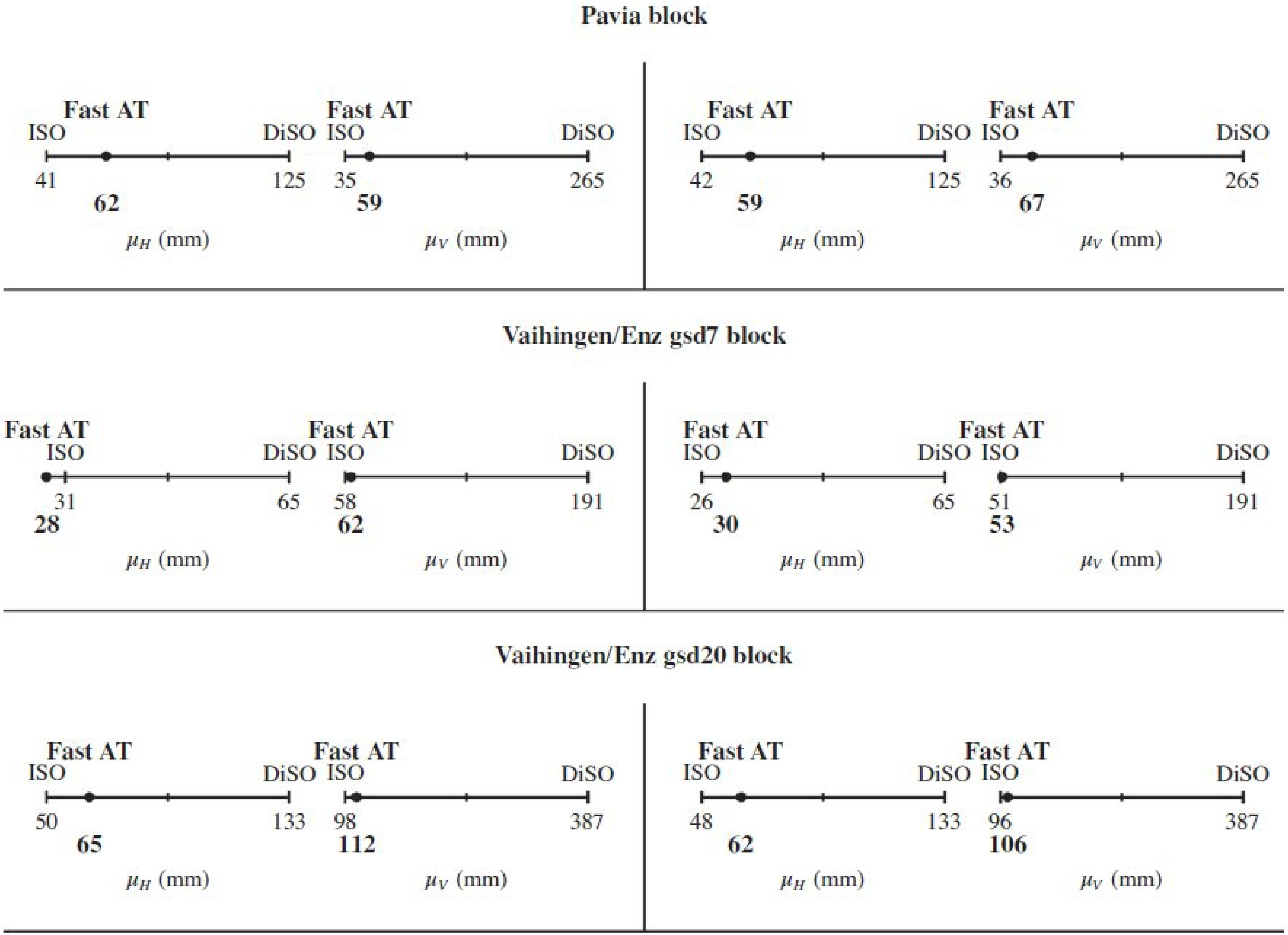
○ Image and tPA Aerial Control

● Ground Control Point (GCP)

□ Image with one or more photo-measurements

Fast AT block: 18 + 13 + 20 + 12 images, photo-measurements in 2 + 3 + 3 + 2 images, 2 sub-blocks, no need for image/strip overlap, image overlap recommended in areas with GCPs.

SIMPLIFICATION OF IMAGE MATCHING



CONCLUSIONS

1. on-going progress in motion sensing with cost reduction
   - GNSS infrastructure
   - inertial sensing
   - timing
2. on-going progress in trajectory determination

   (geomatic, navigation & robotics community)
   - trajectory-level error models
   - sensor-level error models
3. better ways of trajectory exploitation

DO NOT MISS THE

February 10-12, Lausanne, EPFL - www.eurocow.org