ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

AHORN VEYSONNAZ 2018

SWISS INSTITUTE OF NAVIGATION ION-CH

OVAIN

DEUTSCHE GESELLSCHAFT FÜR ORTUNG UND NAVIGATION E.V.

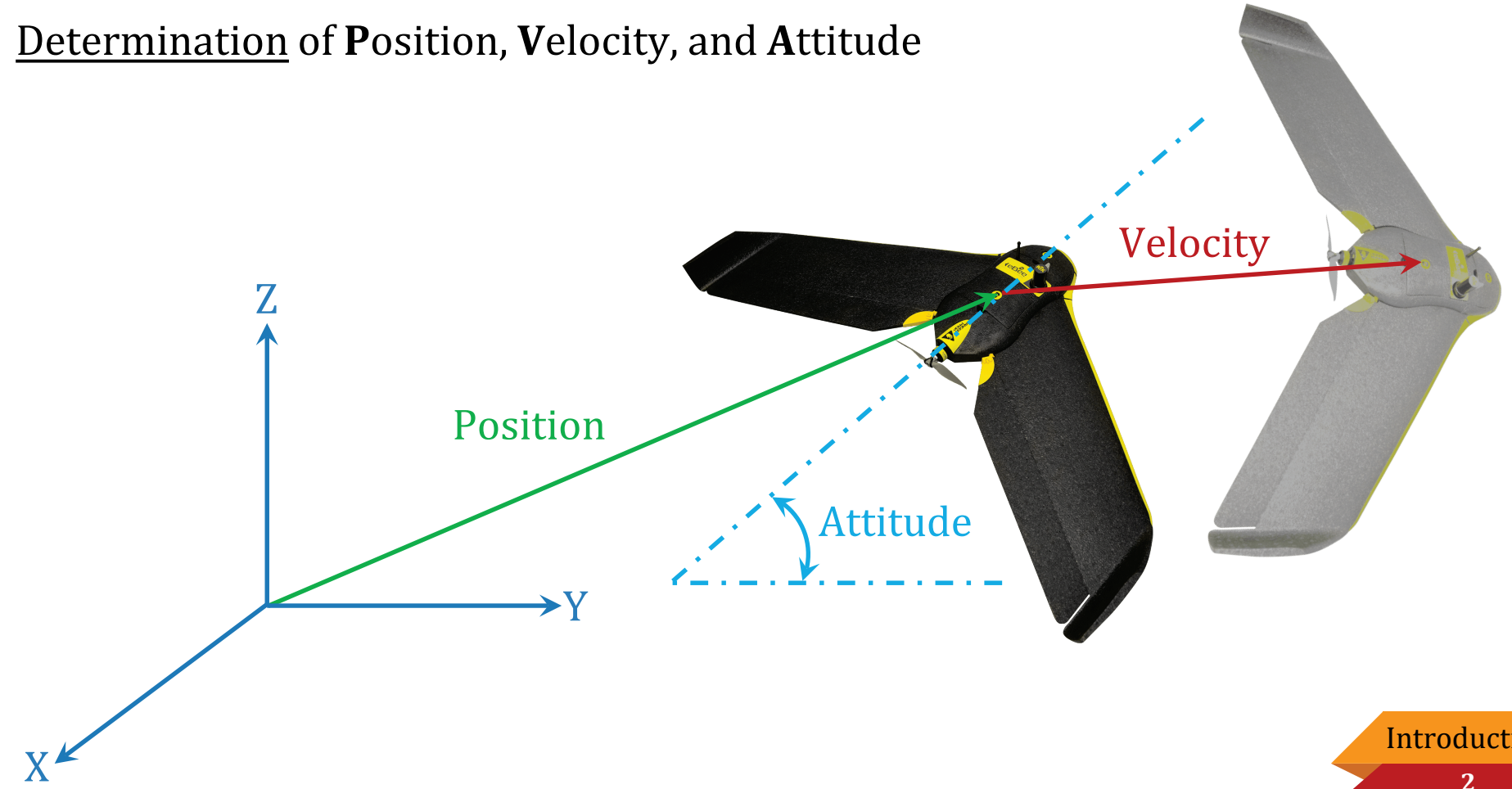
A New Paradigm for

Integrated Navigation of UAVs Based on Vehicle Dynamic Model

Mehran Khaghani & Jan Skaloud

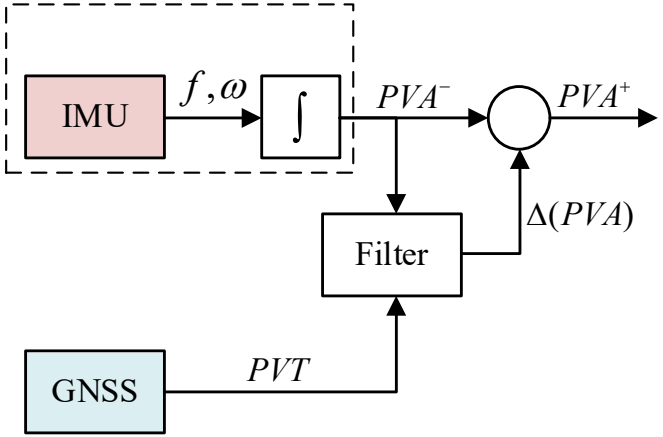
Navigation

Determination of **P**osition, **V**elocity, and **A**ttitude



Integrated Inertial and Satellite Navigation (INS-GNSS)

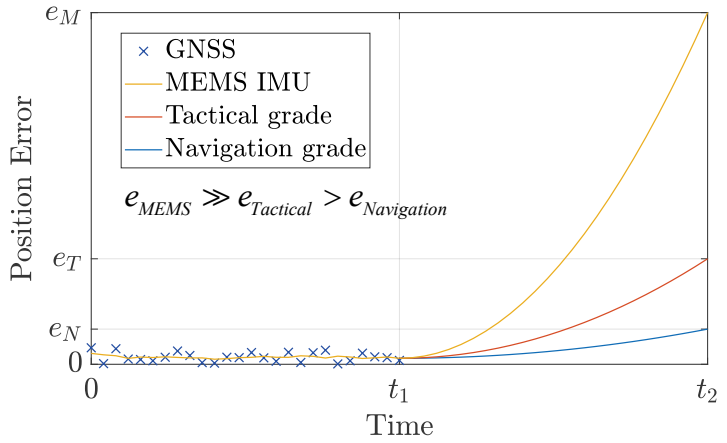
- As old as GPS (>30 years)
- On most UAVs today (outdoor)



INS: Inertial Navigation System
GNSS: Global Navigation Satellite System
GPS: Global Positioning System (American GNSS)
UAV: Unmanned Aerial Vehicle
IMU: Inertial Measurement Unit
PVA: Position, Velocity, Attitude
PVT: Position, Velocity, Time
MEMS: Micro-Electro-Mechanical Systems

Problem 1: GNSS outage

PVA solution will drift over time

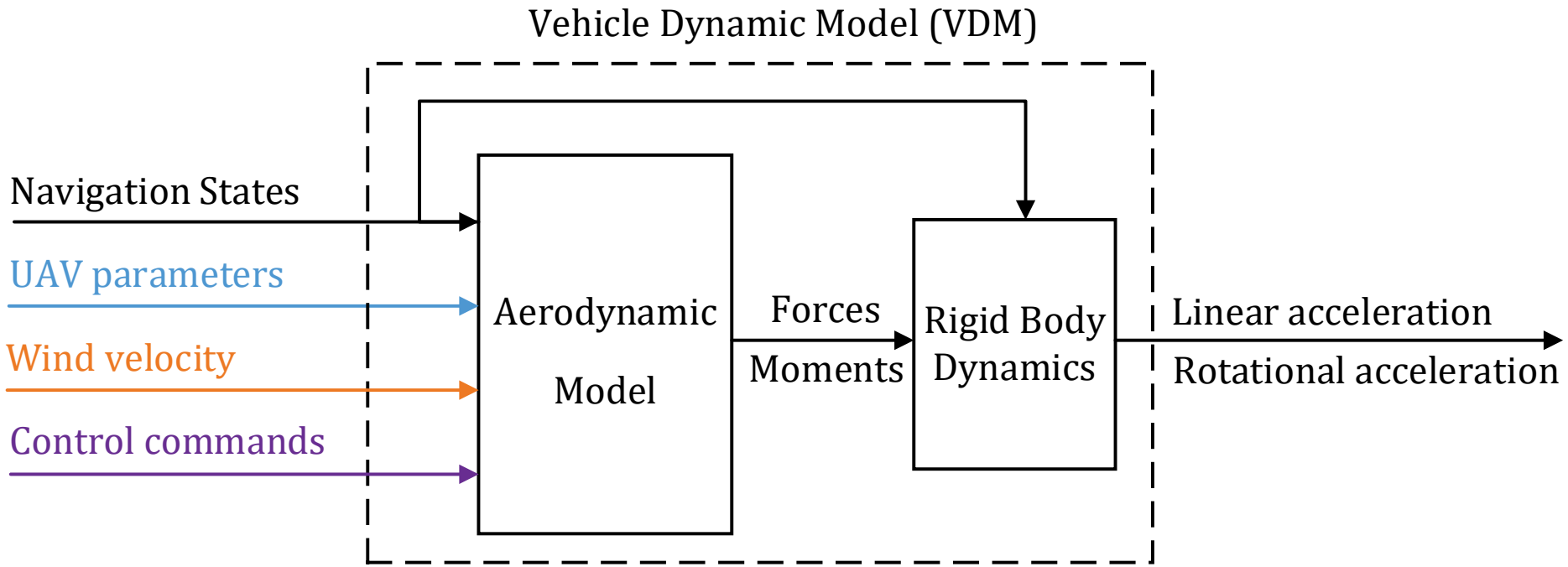


Problem 2: IMU failure

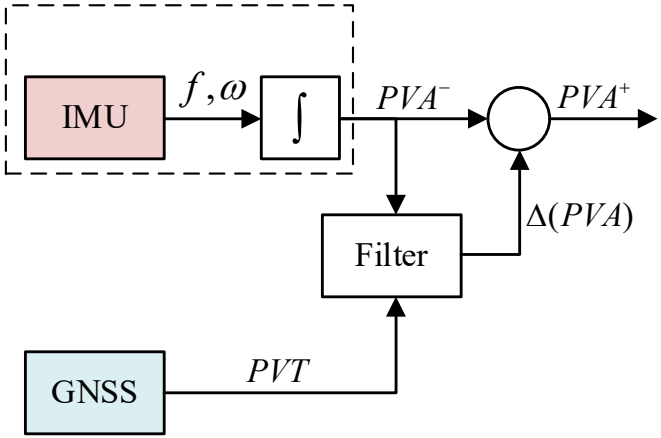
Nothing will work!

Our Proposition

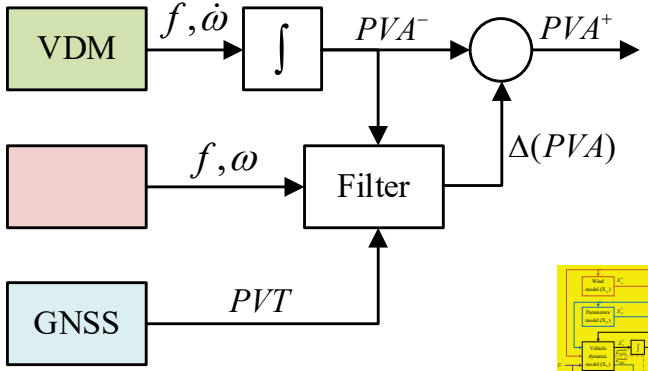
Using VDM in navigation

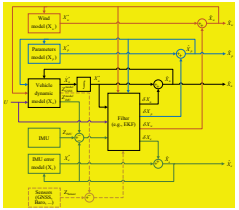


From INS-based to VDM-based Navigation



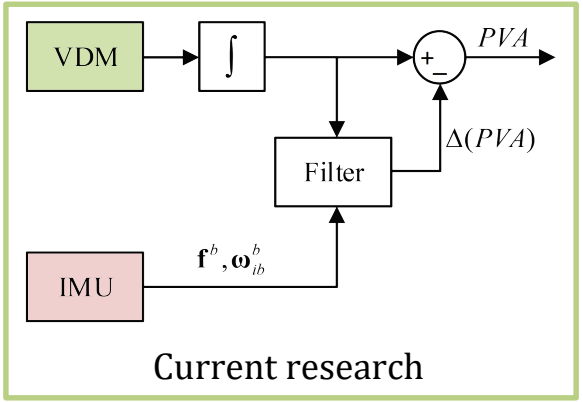
- Platform independence
- Low computational cost
- Sensor (IMU) in process model
  - IMU failure
- Physical constraints





- VDM in process model
- Physical constraints
- No IMU data integration
- Sensor setup
- Self calibration
- Platform dependence
- Higher computational cost (PC: 1.7 to 2.7 times)

Some Other Architectures

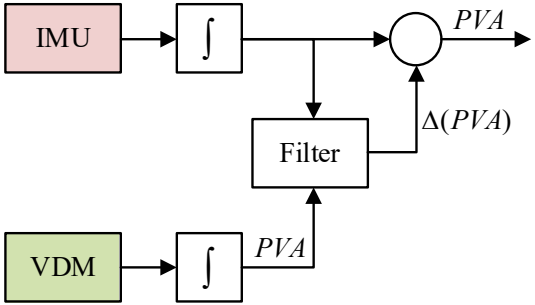


Current research

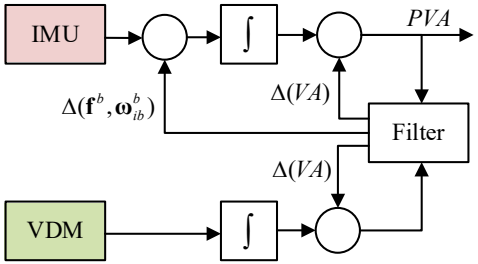
Common issues:

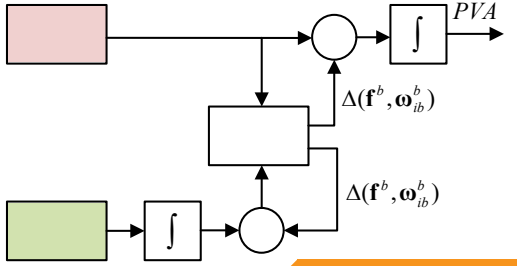
- No wind
- No self calibration
- Partial VDM
- No significant improvement in **experiments**

Still **INS**-based…



Koifman 1999





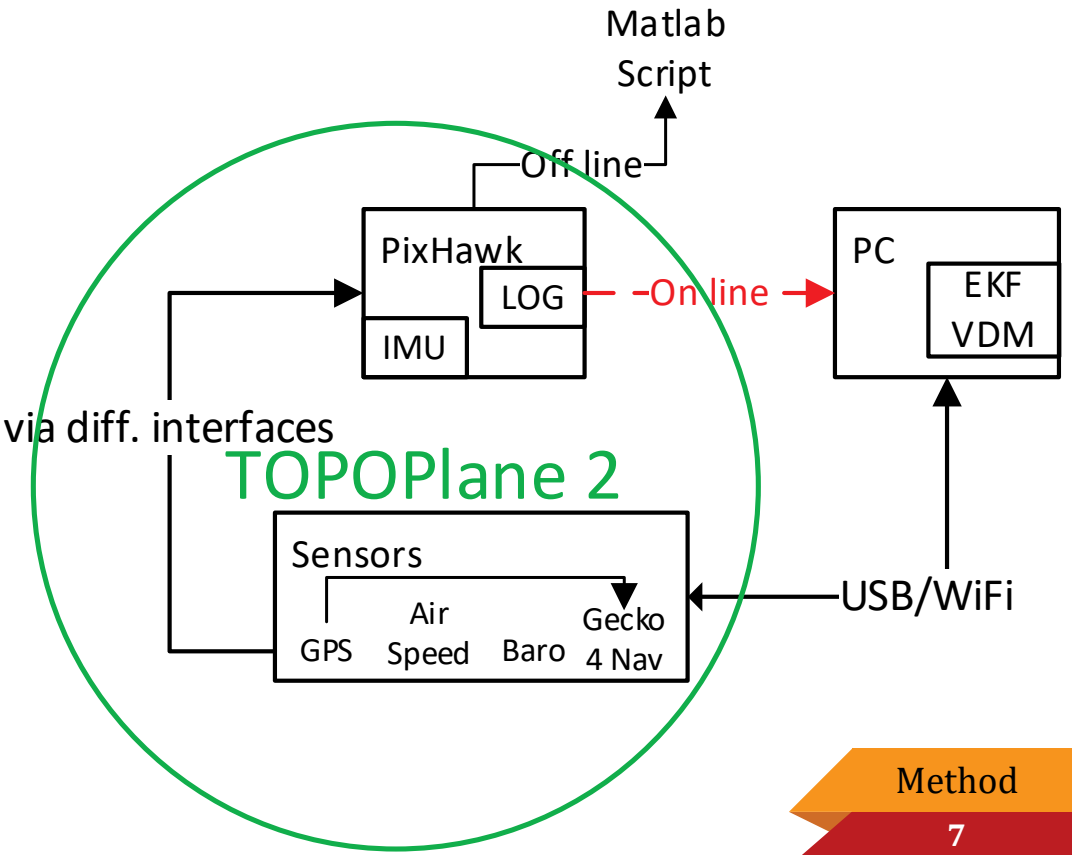
Bryson 2004

Experimental Setup

Aircraft & Sensors

Payload capacity	0.8 kg
Flight endurance	45 minutes
Nominal airspeed	15 m/s

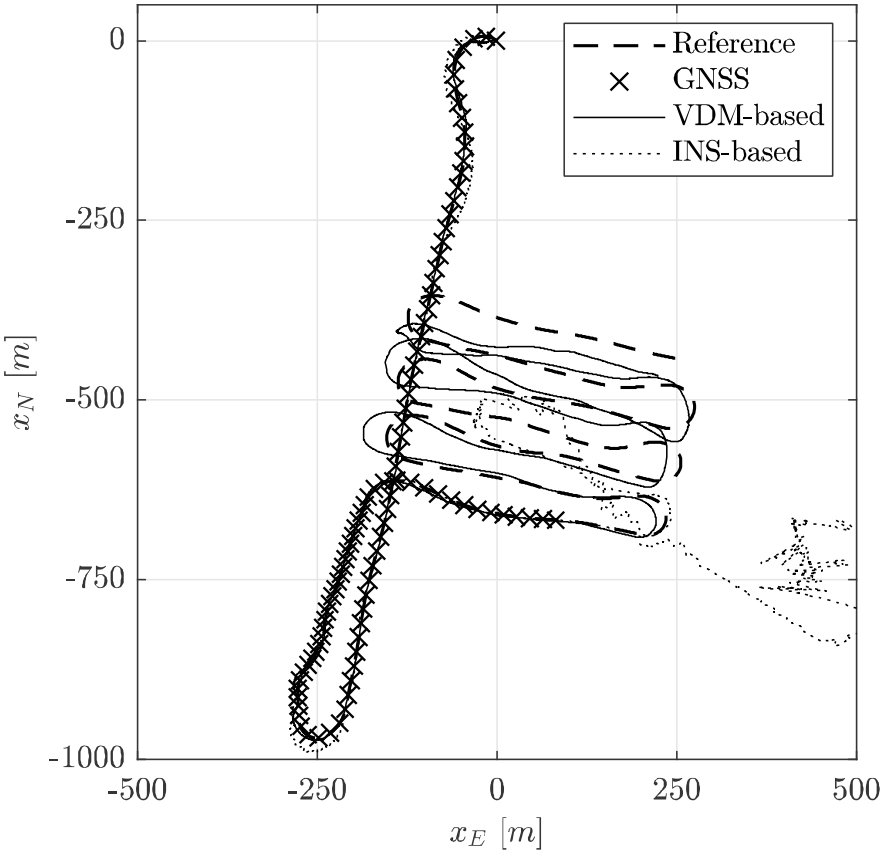
Connections



GNSS Outage: Emulation Scenario

- Waypoints from real flight
- 3D wind velocity from real data
- Error statistics of real sensors
- Flight simulation
  - ✓ Sensor data
  - ✓ Reference data
- 100 Monte-Carlo runs

MEMS IMU
Standalone GNSS

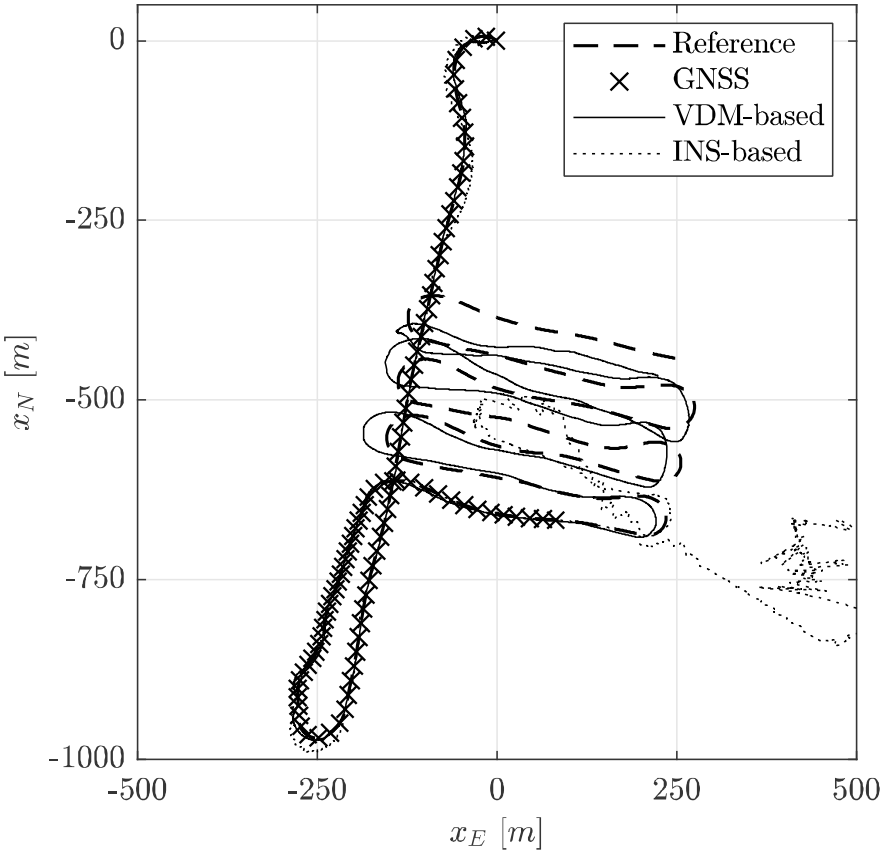


GNSS Outage: Experimental Scenario

VDM parameters calibration:

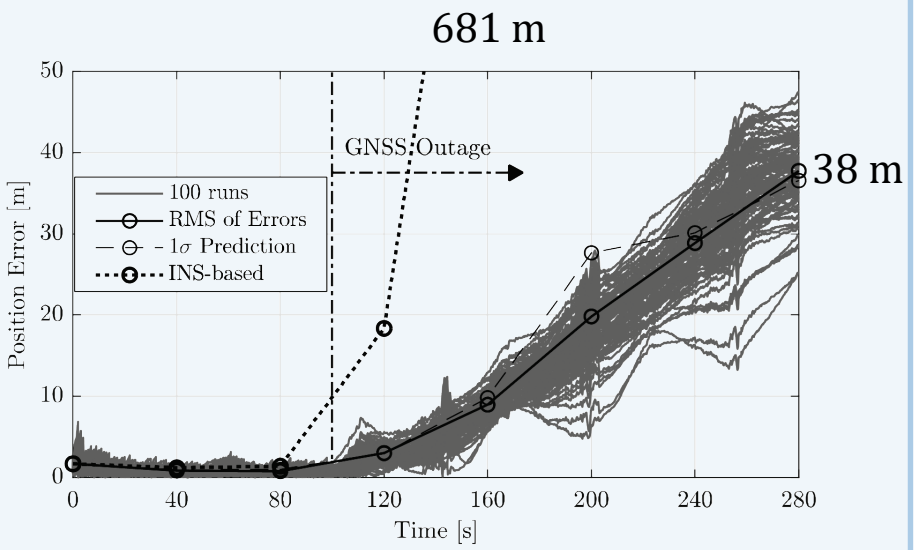
- On a separate flight:
- Start with nominal values in simulations
- IMU and cm-level GNSS data fused
- Navigation states as observations
- VDM parameters estimated

MEMS IMU
Standalone GNSS

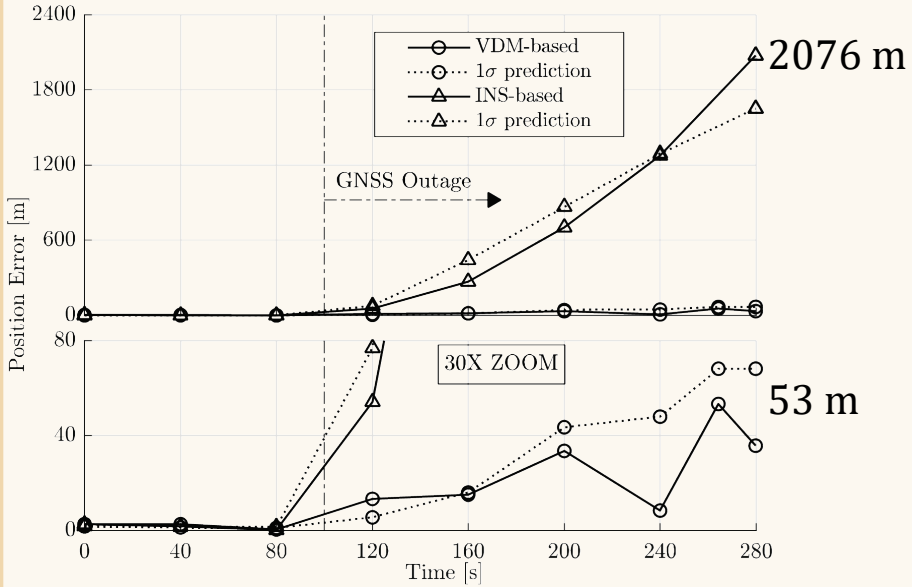


GNSS Outage: Emulation vs Experimental Scenario

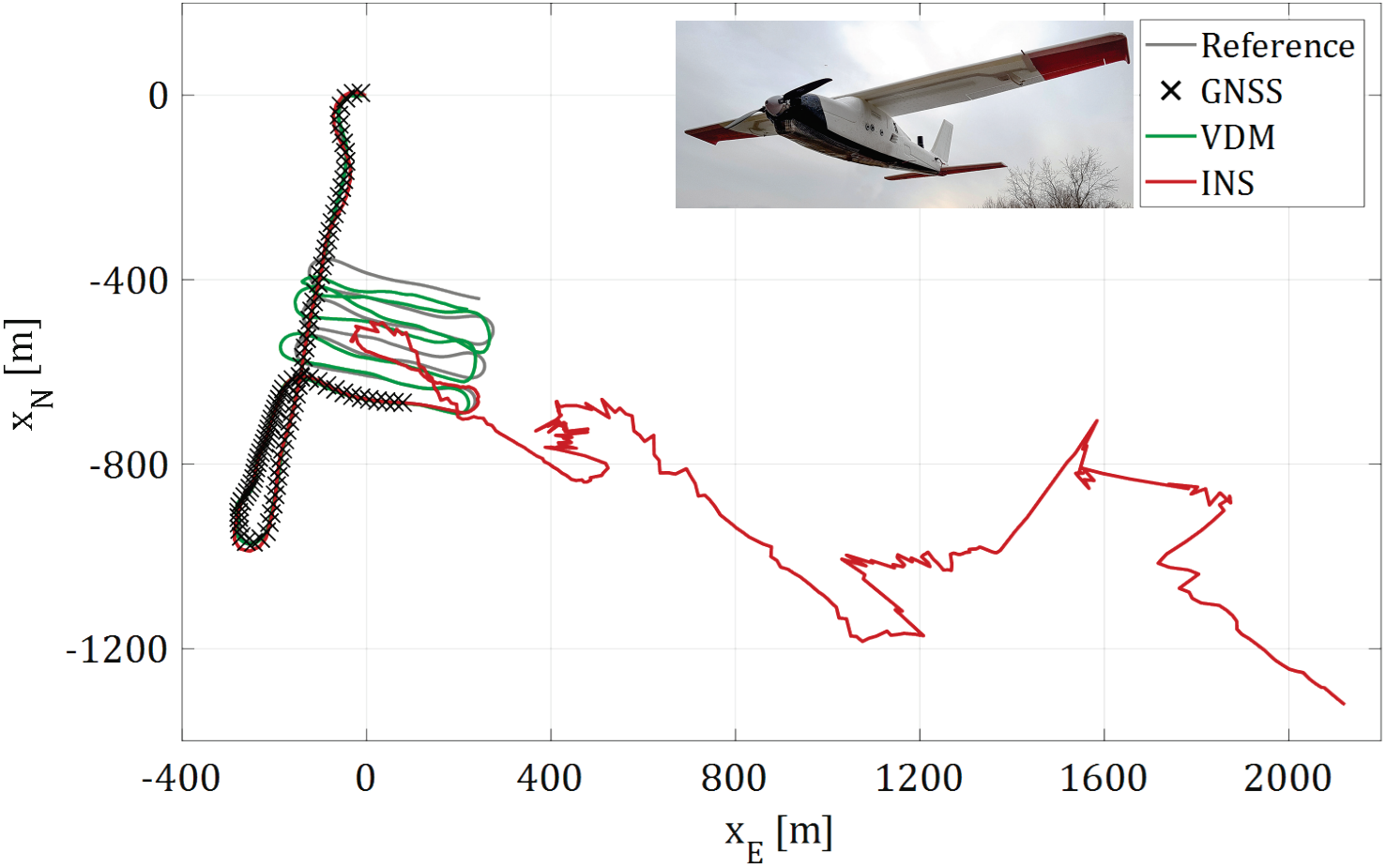
Emulation



Experiment



GNSS Outage: Experimental Scenario



IMU failure: Emulation Scenario

- Waypoints from real flight
- 3D wind velocity from real data
- Error statistics of real sensors
- Flight simulation
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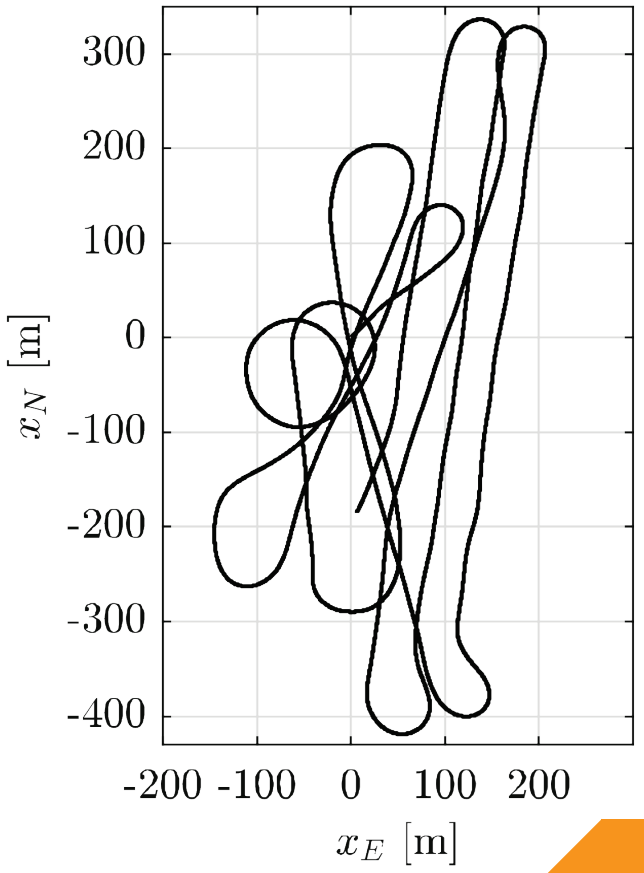
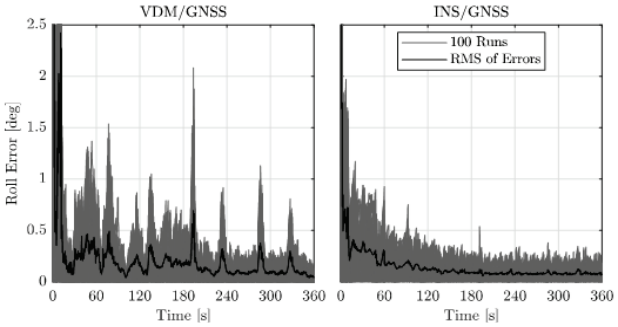
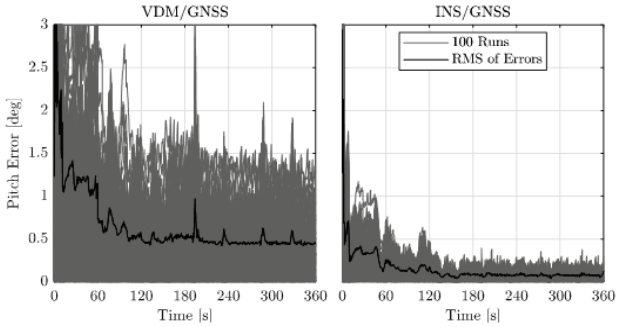
MEMS IMU
Standalone GNSS

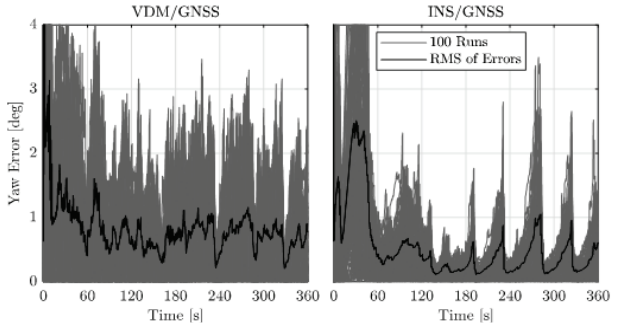


IMU failure: Emulation Scenario

100 Monte-Carlo runs







Navigation type	Roll error[°]		Pitch error[°]		Yaw error[°]	
	$t \leq 60s$	$t > 60s$	$t \leq 60s$	$t > 60s$	$t \leq 60s$	$t > 60s$
VDM/GNSS	3.70	0.69	6.87	0.97	5.13	1.61
INS/GNSS	2.90	0.30	2.94	0.20	5.35	1.05

IMU failure: Experimental Scenario

VDM parameters calibration:

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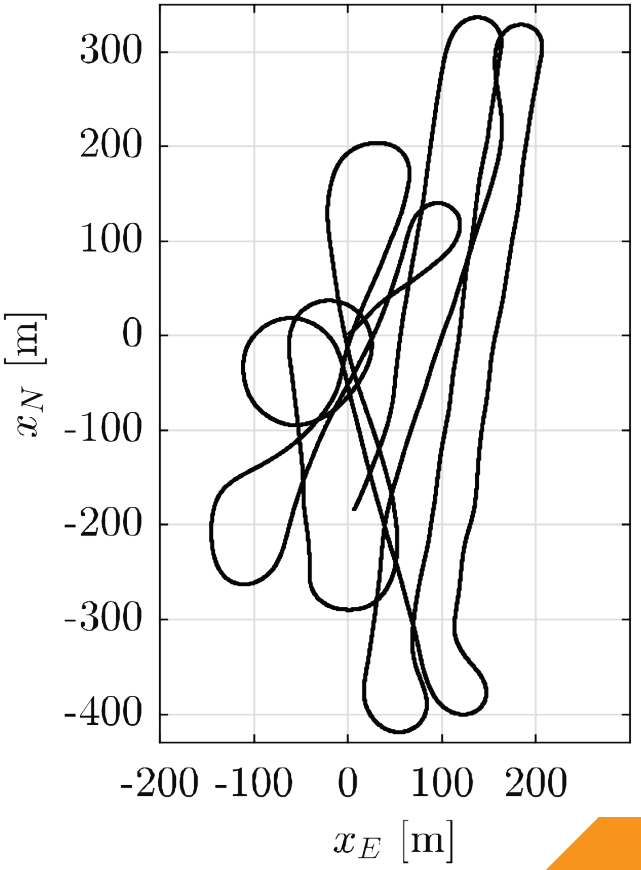
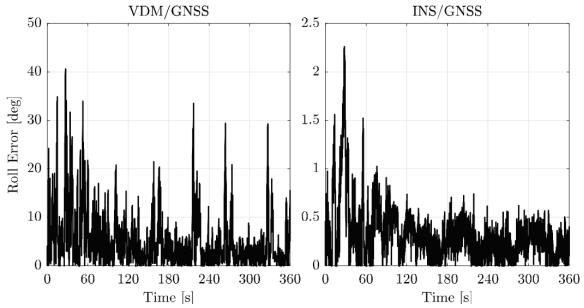
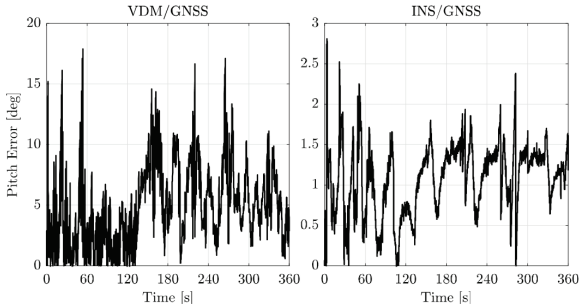
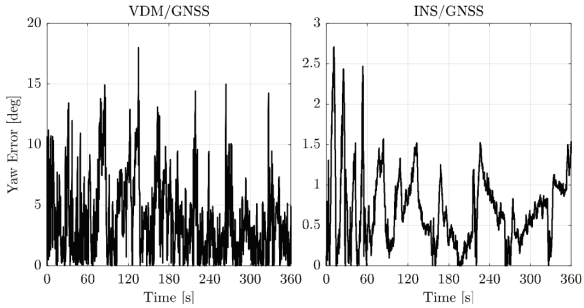


IMU failure: Experimental Scenario







Navigation type	Roll error[°]		Pitch error[°]		Yaw error[°]	
	Max	Mean	Max	Mean	Max	Mean
VDM/GNSS	40.6	5.3	17.9	4.8	18.0	3.8
INS/GNSS	2.3	0.3	2.8	1.1	2.7	0.7

The main suspect: Residual error in VDM parameters estimation

Solution: Absolute attitude reference via photogrammetry (TBD)

Conclusion & Outlook

- Realization matters!
  - Estimation architecture, VDM/IMU priors & on-line re-fining
  - Platform, actuators, IMU + mount + models, time-stamping
- Attitude estimation
  - Emulation: <1° for roll & pitch, <2° for yaw
  - Experiment: Mean ~5°, Max ~20-40° => Need to improve VDM calibration

Acknowledgements: DDPS – CTI (Innosuisse)

- GNSS outage, 2.2 kg fixed-wing MAV
  - Emulation: up to 100x better without additional sensor
  - Experiment: 20-40x better (e.g., @3min: 50 m vs 2 km)
- Outlook
  - Attitude reference from photogrammetry
  - Redundant IMUs
  - Direct actuation measurements
  - Online implementation

Thank you for your attention

- **Concept / Monte-Carlo simulation**
  [Navigation, 2016] Autonomous Vehicle Dynamic Model-Based Navigation for Small UAVs
- **Enhanced modeling / Experiments**
  [Robotics and Autonomous Systems, 2018] Assessment of VDM-based Autonomous Navigation of a UAV under Operational Conditions
- **Mapping**
  [ISPRS Archives, 2016] Application of Vehicle Dynamic Modeling in UAVs for Precise Determination of Exterior Orientation
- **Wind effects**
  [ION GNSS+, 2016] Evaluation of Wind Effects on UAV Autonomous Navigation Based on Vehicle Dynamic Model
- **Sensitivity Analysis**
  [IEEE Transactions TAES, 2018 (under review)] Global Sensitivity Analysis of VDM-based Navigation for UAVs