A Drone-Based Gravity Measurement System

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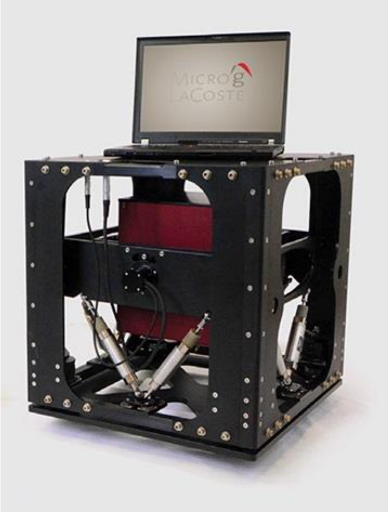
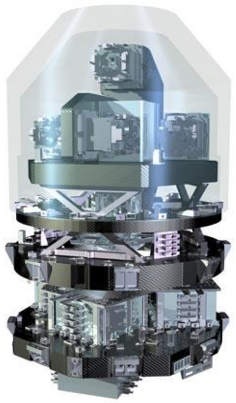
Part I: Moving-Base Gravimetry

Or how to do gravity observations from a moving platform

Gravity Instruments

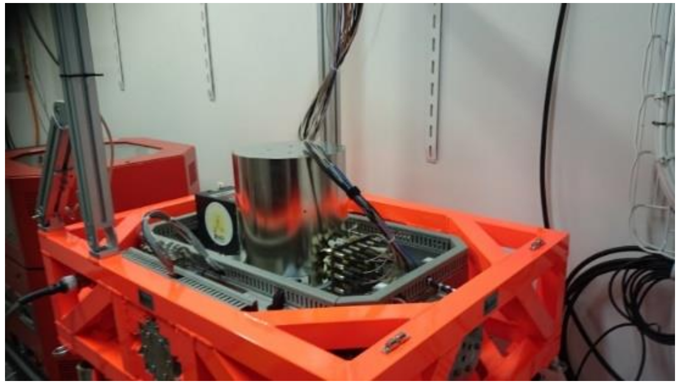


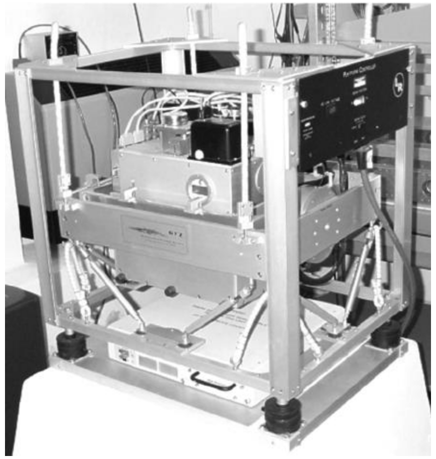


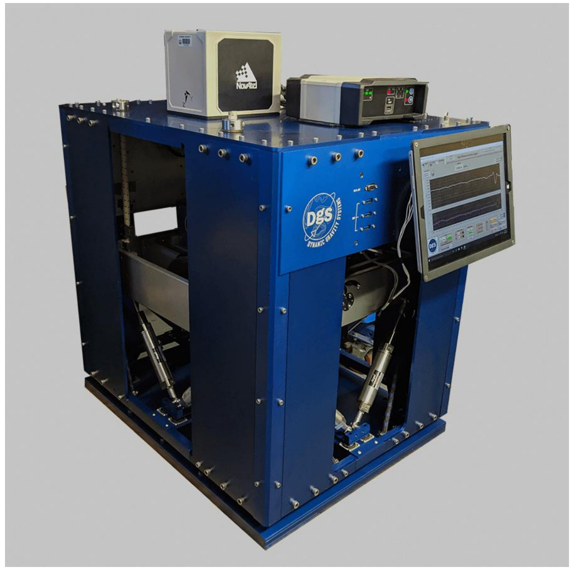
We measure gravity using a gravimeter!

There are many different measurement technologies

But all gravimeters are essentially accelerometers!







How Does the Gravimeter Work?

<u>Basic concept:</u>

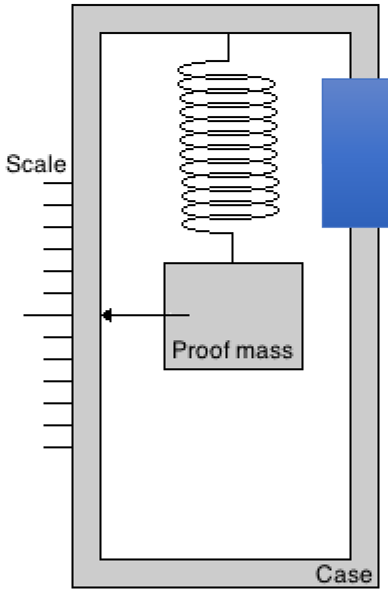
- Proof mass
- Ideal spring
- Pick-off device

<u>Apply a (contact) force:</u>

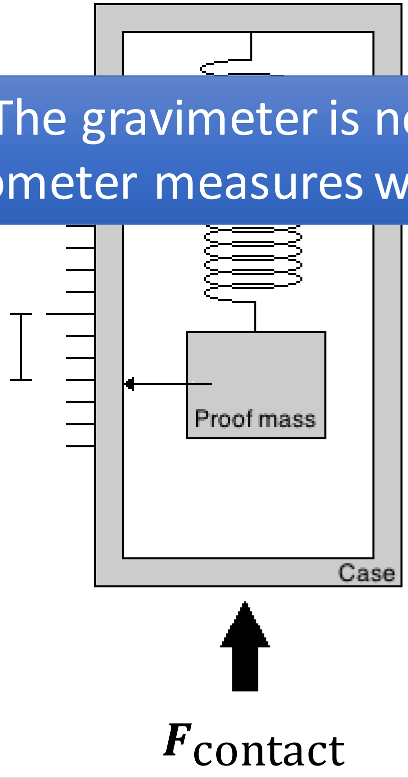
- Casing accelerates
- Spring force compensation
- Pick-off displacement

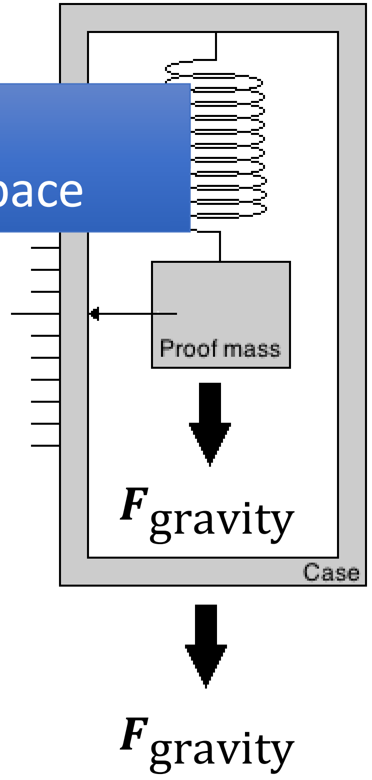
<u>Apply gravity:</u>

- Affects both casing and proof mass
- No pick-off displacement



SPOILER: The gravimeter is not sensitive to gravity!!!
→ An accelerometer measures with respect to inertial space

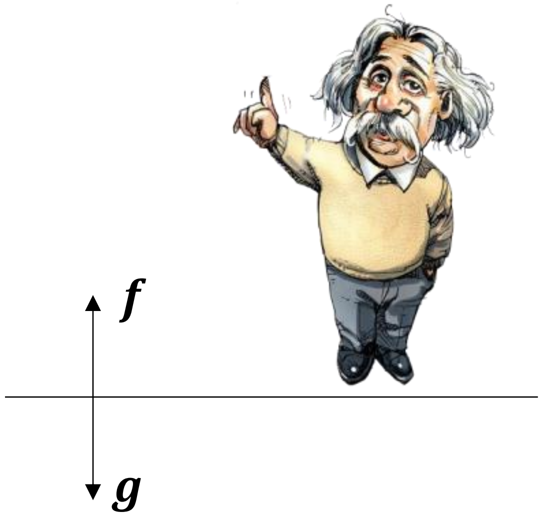




What are We Measuring Then?

Scenario: An observer is standing in this room

Weak equivalence principle!



The observer will experience two forces:

1. Gravity: Gravitational pull of the Earth + centrifugal force
2. The (equal and opposite) reaction force from the floor

$$m\ddot{\boldsymbol{r}} = m\boldsymbol{g} + m\boldsymbol{f} \quad \Leftrightarrow \quad \boldsymbol{f} = \ddot{\boldsymbol{r}} - \boldsymbol{g}$$

Specific force	Kinematic acceleration	Gravitational acceleration
This is what the accelerometer measures	Acceleration due to movement	Newtons law of gravitation

The gravimeter measures gravity with opposite sign

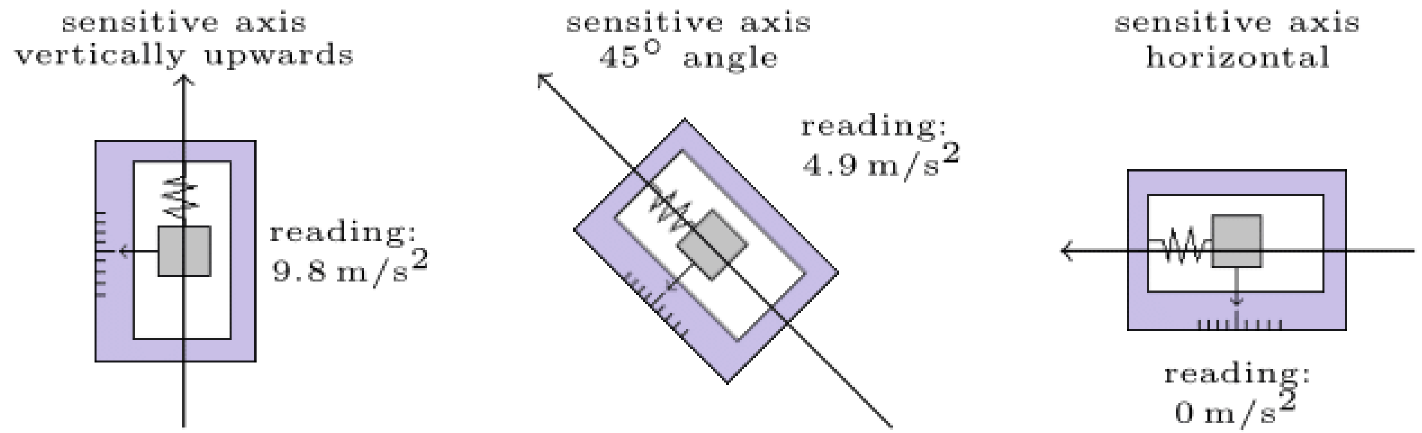
Terrestrial gravimetry

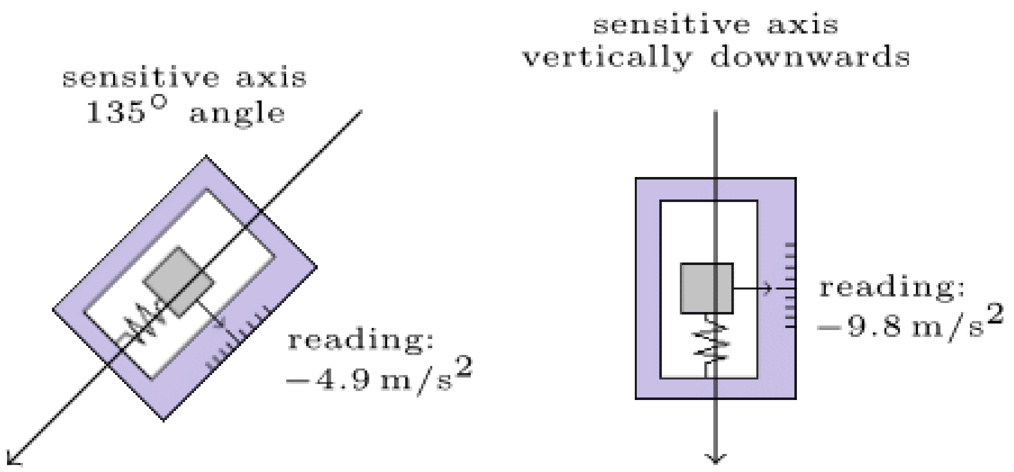
The observer/instrument is not moving:

$$\ddot{\boldsymbol{r}} = \boldsymbol{0} \quad \Rightarrow \quad \boldsymbol{f} = -\boldsymbol{g}$$

Orientation of the Gravimeter

Imagine a gravimeter/accelerometer on the surface of the Earth:





The accelerometer measures accelerations along a single sensitive axis!

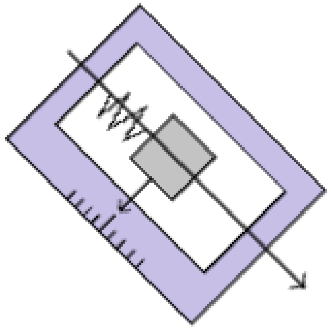
Notice opposite sign!

The accelerometer does not sense gravity directly

Only the counter-reaction to gravity (contact force on the casing)

The Fundamental Problems of Gravimetry

1. Determine the sensor orientation

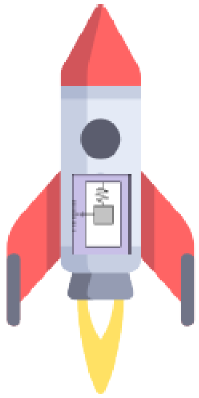


The fundamental equation of gravimetry

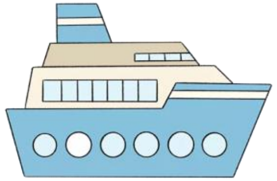
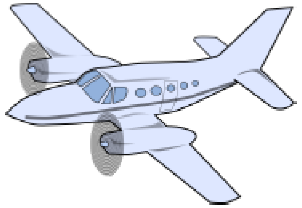
$$\mathbf{g} = \ddot{\mathbf{r}} - \mathbf{C}\,\mathbf{f}$$

2. Correct for the kinematic component

contains **two fundamental issues**:



Stationary vs. Moving-Base Gravimetry

	Stationary 	Moving-Base  
<u>Problem 1:</u> Determine sensor orientation	 levelling bubble  tripod 	 horizontal accelerations = false plumb line  Tripod must be adjusted continously 
<u>Problem 2:</u> Separate kinematic and gravivational components	No movement!	Aircraft maneovering Wind effects Vibrations Physical distortions etc.

Problem 1: Sensor Orientation

There are two common approaches to handle the orientation:

1. Mechanical – Mounting the accelerometer on a stabilised platform

2. Computational – The accerometer is mounted directly on the chassis (strapdown)

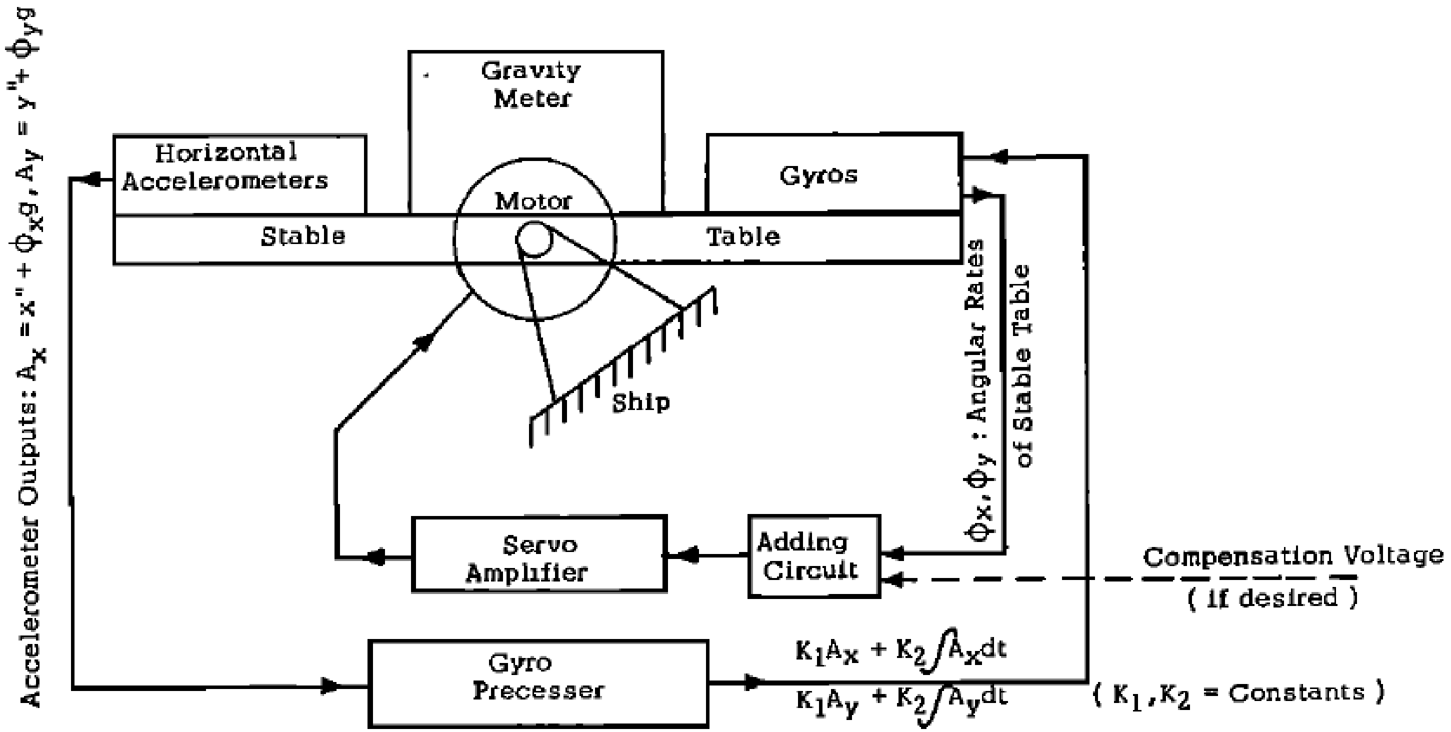
Problem 1: Sensor Orientation

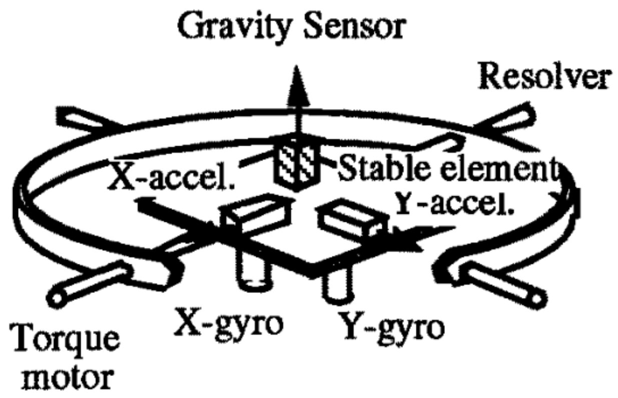
The Stabilized Platform

1. Mechanical – Mounting the accelerometer on a stabilised platform

- Gyroscopes measure rotational motion and forward information to torque motors
- Torque motors will compensate mechanically by rotating platform

→ Sensor is isolated from aircraft rotations





Determining the plumb-line direction

- Horizontal accelerations are measured
- At constant velocity, horizontal accelerations should average out in time

→ Horizonal accelerations filtered in time

→ Any misalignment is derived from filtered accelerations (and corrected for) (will not work during turns)

From LaCoste, Measurement of Gravity at Sea and in the Air, Reviews of Geophysics (1967)

Problem 1: Sensor Orientation

The Strapdown Configuration

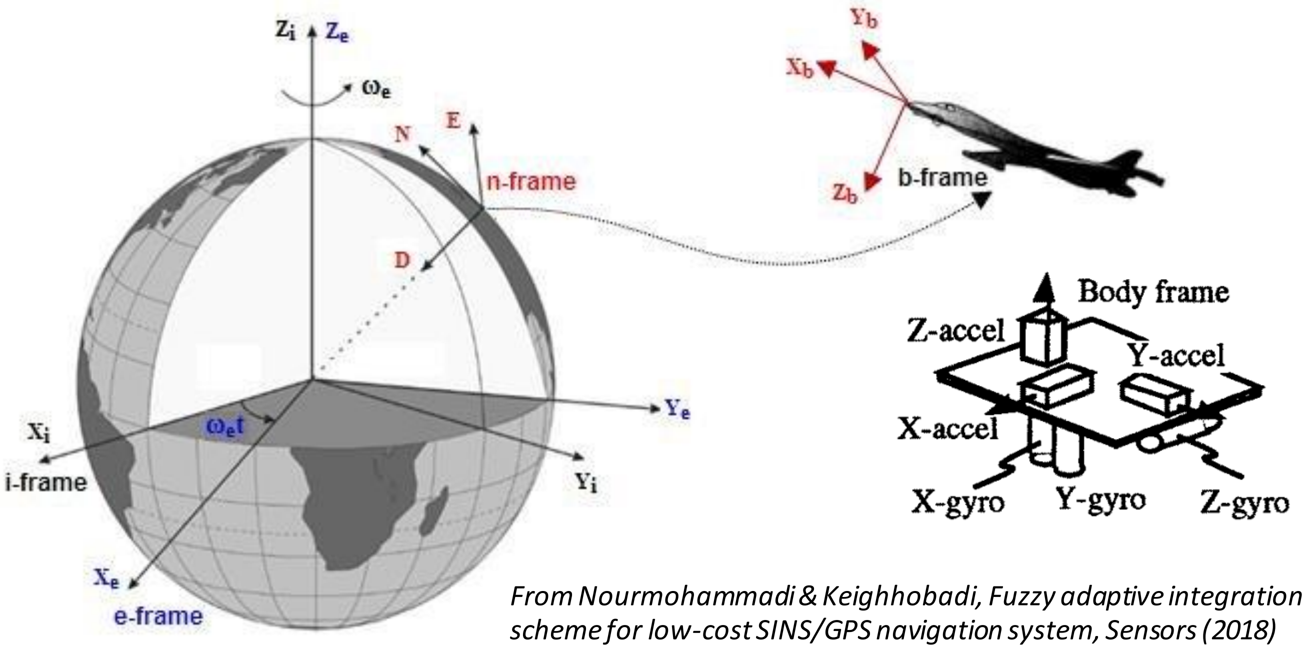
2. Computational – The accerometer is mounted directly on the chassis (strapdown)

- Gyroscopes measure rotation and stores information digitally

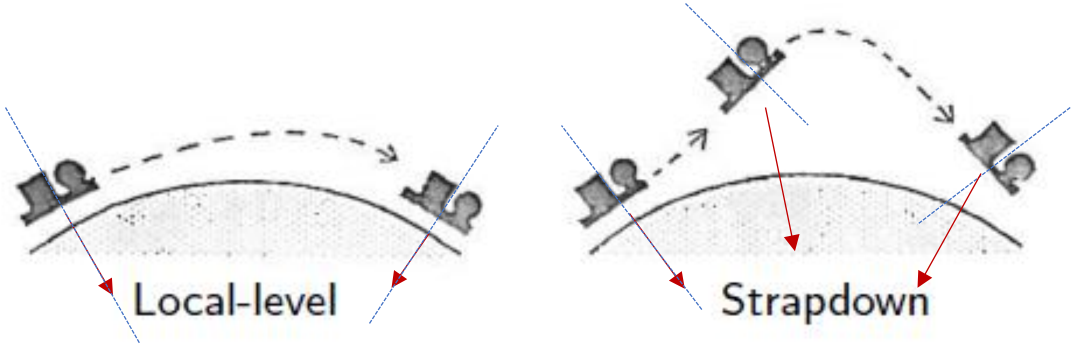
→ The orientation can be determined computationally post-mission

- A triad of perpendicular accelerometers measure the full vector

→ The body-frame vector can be decomposed onto the desired direction post-mission



From Nourmohammadi & Keighhobadi, Fuzzy adaptive integration scheme for low-cost SINS/GPS navigation system, Sensors (2018)



Direction of sensitive axis

Direction of gravity / plumb-line

Problem 2: Kinematic Accelerations

- Both gravimeter and GNSS systems measure large accelerations on the order of m/s^2
- The variation in the gravity field is on the order of $\text{mGal} = 10^{-5} m/s^2$

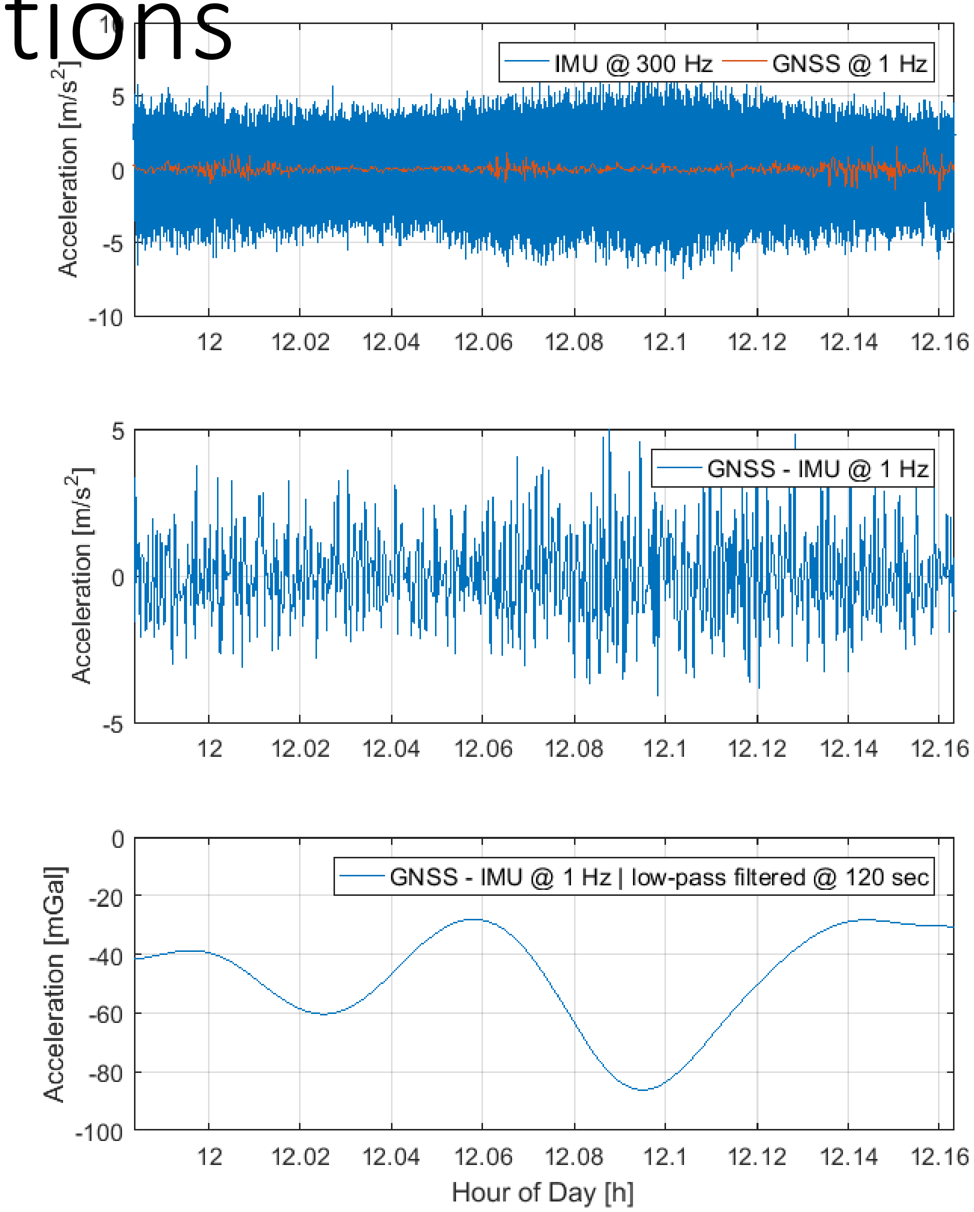
Form differences $\ddot{\mathbf{r}} - \mathbf{f}$

- Signal is still on the order of m/s^2 (signal-to-noise ration is very small)

Apply low-pass filter

- Gravity variation is on the order of mGal

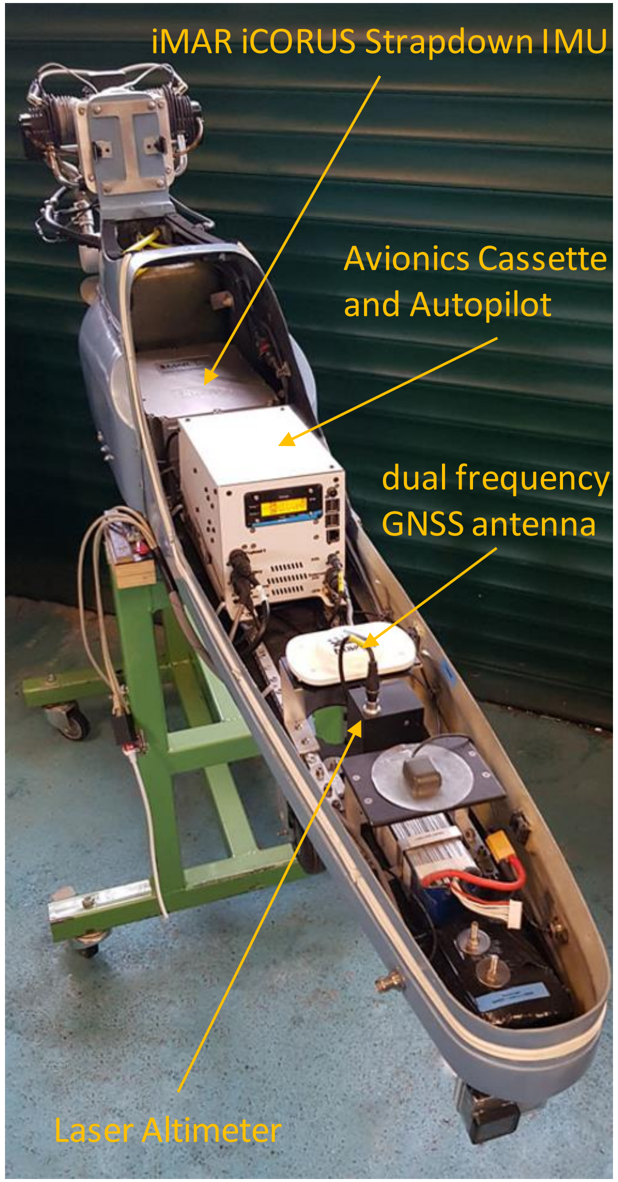
Filter design is very important!



Part II: Towards a Drone-Based Gravity System

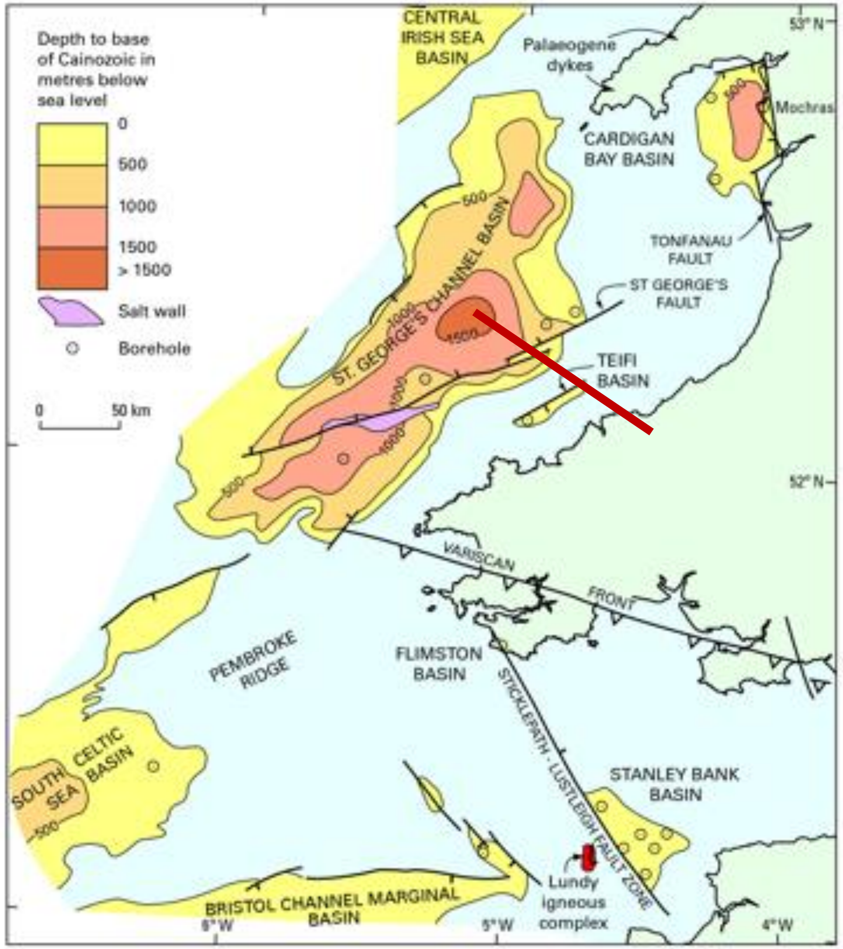
Prion Mk3 Test (Previous Project - first attempt)

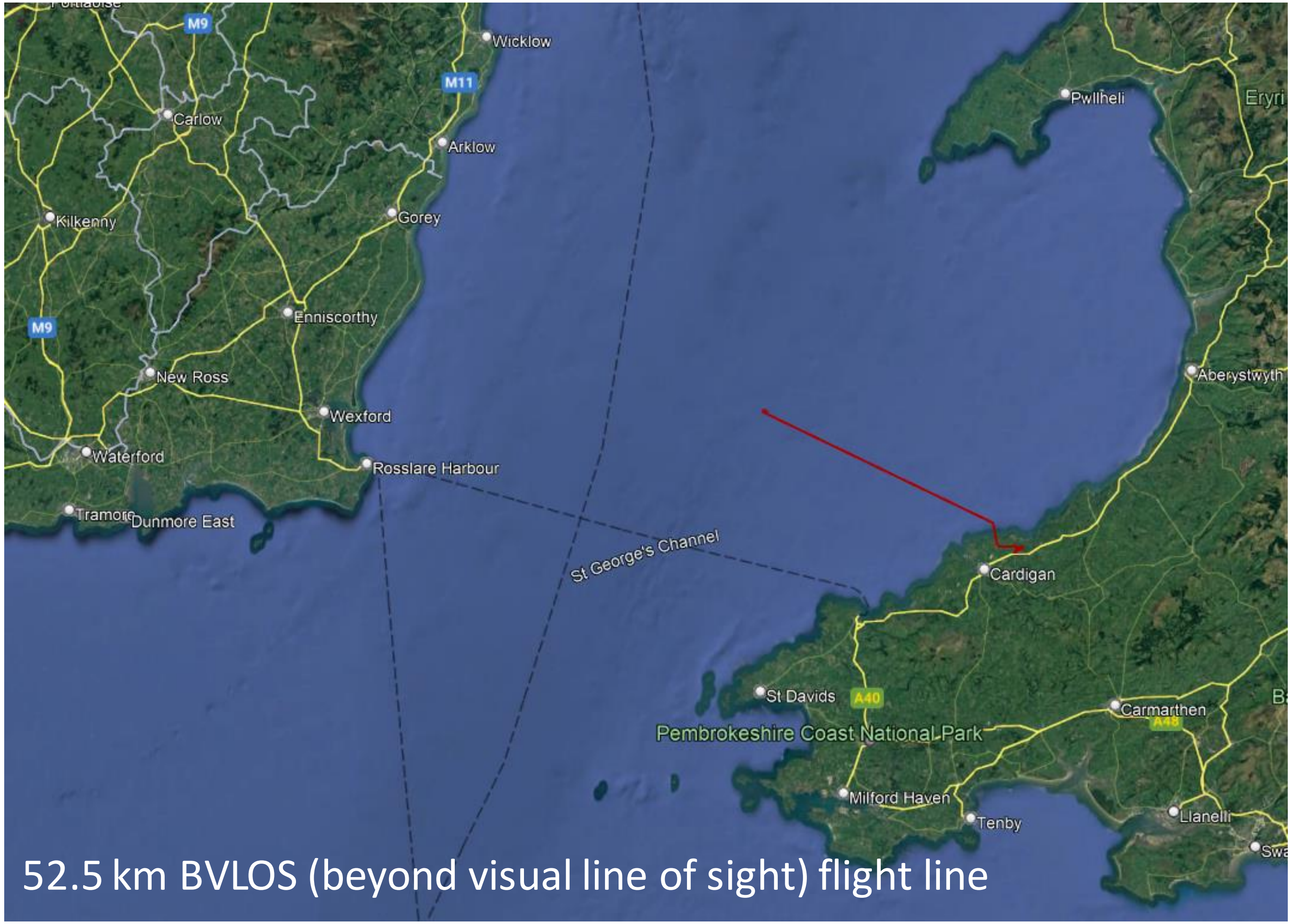
UAVE Prion Mk3 UAV	
Wingspan	3.8 m
Length	3.0 m
Weight	30 kg
Operational time	12 hours
Operational range	1000 km
Payload	Max. 15 kg
Engine type	Petrol



Prion Mk3 Test (Previous Project)

Structural map:
Expected gravity anomaly



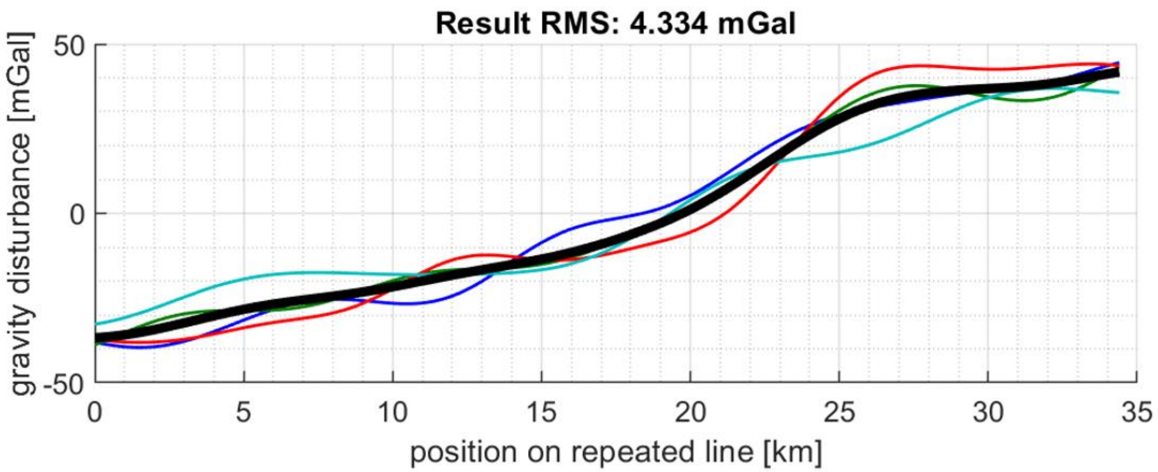


52.5 km BVLOS (beyond visual line of sight) flight line

Prion Mk3 Test (Previous Project)

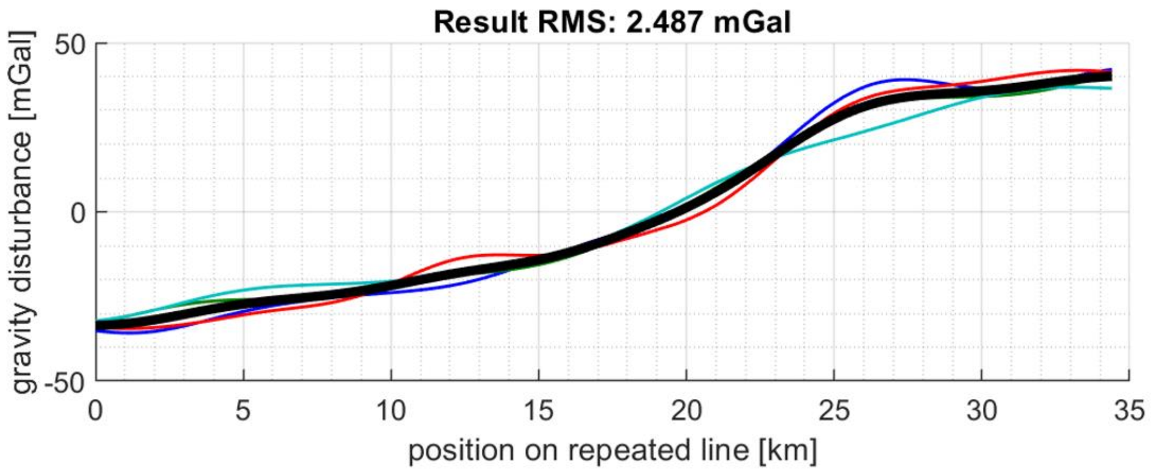
First results

- Flights characterised by large attitude variations
- Dynamics larger than aircrafts
- Gives processing challenges



Fine Tuned Results

- Internal IMU errors are estimated based on repeat line (least-squares difference minimized)
- Additional errors are related to the relative difference between internal sensors (geometrical configuration)
- Such errors are usually not relevant for aircrafts, but might be for high-dynamic environments.



Lessons Learned

- We got some decent gravity results …. but it still remains an open question how to mitigate errors.
  - Maybe processing development
  - Maybe changing the platform

In the DroneSOM project we will experiment with both fixed-wing and multi-rotor UAVs. And we will look for other sensors.

- Getting permission to fly this kind of UAV took a long time (more than a year).

In the DroneSOM project we will aim at smaller UAVs, which makes the process easier.

Sensors on the Market

Conclusion:

iMAR is the only realistic option within the project lifetime

	iMAR iNAT-RQH-4001	Fibernetics Triton Navigation-Grade IMU	Thales TopAxyz Grade 0
Accelerometer	**Q-Flex**	**Q-Flex**	**?**
Bias stability	$< 25\ \mu g$	$< 25\ \mu g$	$50\ \mu g$
Scale factor stability	$<$ 100 ppm	$<$ 100 ppm	75 ppm
Gyroscopes	**RLG**	**FOG**	**FOG**
Bias stability	$<$ 0.002 deg/hr	$<$ 0.005 deg/hr	$<$ 0.001 deg/hr
Random walk	$<$ 0.001 deg/$\sqrt{hr}$	$<$ 0.0003 deg/$\sqrt{hr}$	$<$ 0.0016 deg/$\sqrt{hr}$
Scale factor stability	$<$ 5 ppm	~10 ppm	< 15 ppm
Technical details			
Size	187 x 128 x 296 mm	Ø 159 x 178 mm	157 x 102 x 107 mm
Weight	~ 7.9 kg	4.1 kg	2.8 kg
Input voltage	10 – 35 V	18 – 35 V	
Power consumption	$<$ 25 W	$<$ 14 W	$<$ 6 W
Temperature range	−40 to 71 °C	−20 to 60 °C	−40 to 70 °C

We know it works for gravimetry

Heavy

Smaller weight
Accelerometer technology same as iMAR

First sensor not yet ready (start-up company aimed at US market)

Light weight
Low power consumption

Accelerometers highly temperature sensitive
Not complete system (sensor package only, no timing and data collection)

Requirements and Limitations

Flight regulations for getting permission to fly provides the requirements:

- Wing-span below 3 m
- Total weight below 25 kg

IMU weight will reduce in near future
→ Current weight limits practical operation critically
→ Reduced weight will make this method much more useful

Sensor weight is the main limitation of the system:

- iMAR incl. Power cable: 7.20 kg
- GNSS antenna: 0.11 kg
- LiPo battery: 0.31 kg

Total weight: ~7.70 kg (incl. cables)

The GNSS System

We need high-quality GNSS to derive kinematic accelerations!

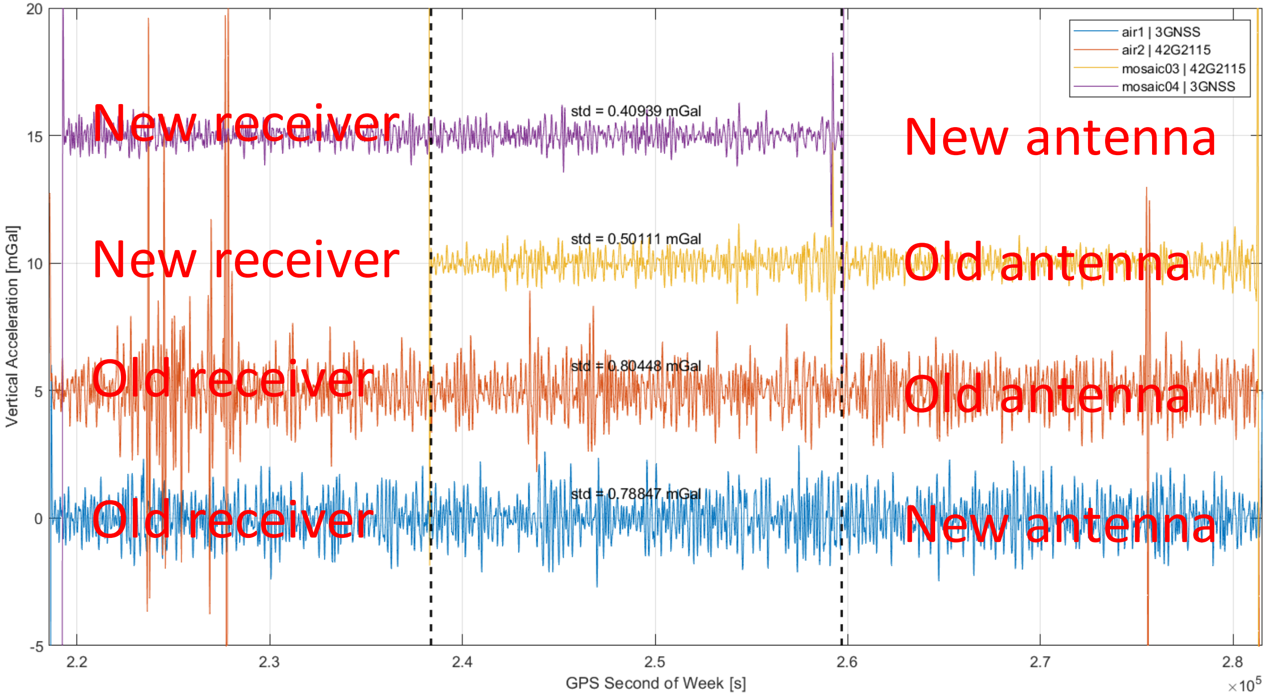
The DTU system for many years:

JAVAD DELTA GNSS Reciever
Size: ≈ 30 × 100 × 150 mm
Weight: ≈ 0.4 kg

NovAtel ANT-532-C Dual Frequency GNSS Antenna
Size: ≈ 30 × 80 × 120 mm
Weight: ≈ 0.2 kg

New multi-constellation system:

Results from static experiment (accelerations should be zero)



The increased number of satellites from more systems seem to improve accelerations

The Fixed-Wing Platform

Finding a suitable platform proved challenging

→ Weight main limitation!

Solution: Custom-made UAV designed around iMAR IMU
Ongoing development by Dines Avitech

Dines UAV-005-DTU	
Wingspan	2.99 m
Length	2.15 m
Weight	25 kg MTOM
Operational time	1,5 hours
Operational range	100 km
Payload	10 kg
Engine type	Gasoline

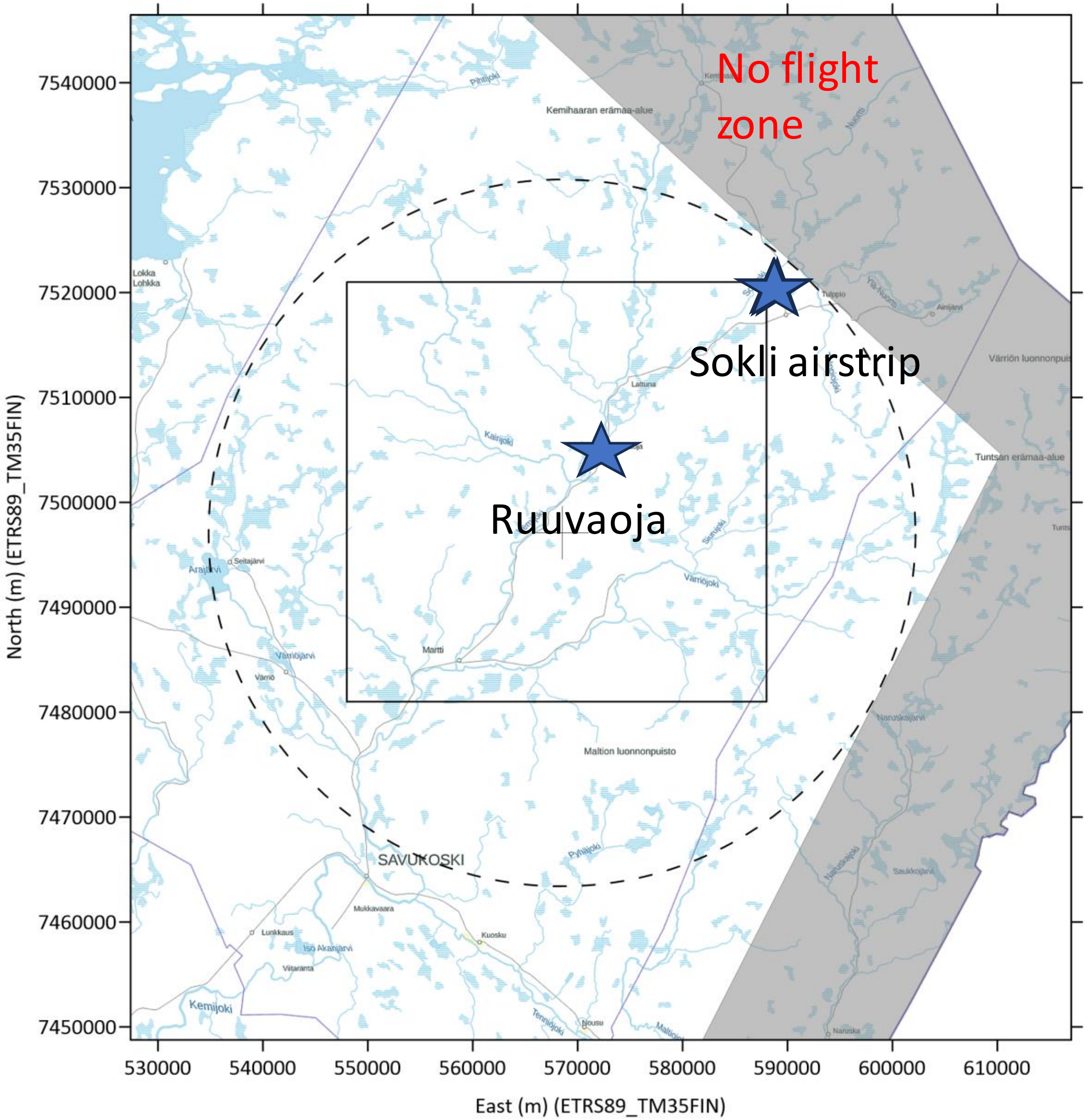

First test flight in March 2023

The "Sokli" Test

- Sokli area – target (large mineralisaton)
- Abandoned airstrip in Sokli to be used

- Finnish civil aviation introduced drone no-flight zone shortly before field campaign

- Need for reconnaisance of suitable drone landing site / runway – not easy (trees, ditches, stones)



The ”Sokli” Test

- Weather miserable: rain, first winter snow … impossible to carry our all planned flights
- Limited range of BVLOS due to radio link
- Max 600 ft AGL restriction from Finnish CAA

Flight tracks – 4 repated flts + 2 parallel

The Multi-Rotor Platform

Finding a suitable multi-rotor platform was done in coorporation with Drone Systems

Arcsky X55	
Wingspan	2.00 m
Length	2.00 m
Weight	25 kg MTOM
Operational time	23 minutes
Operational range	20 km
Payload	7,7 kg
Engine type	Hybrid (Battery or Gasoline)

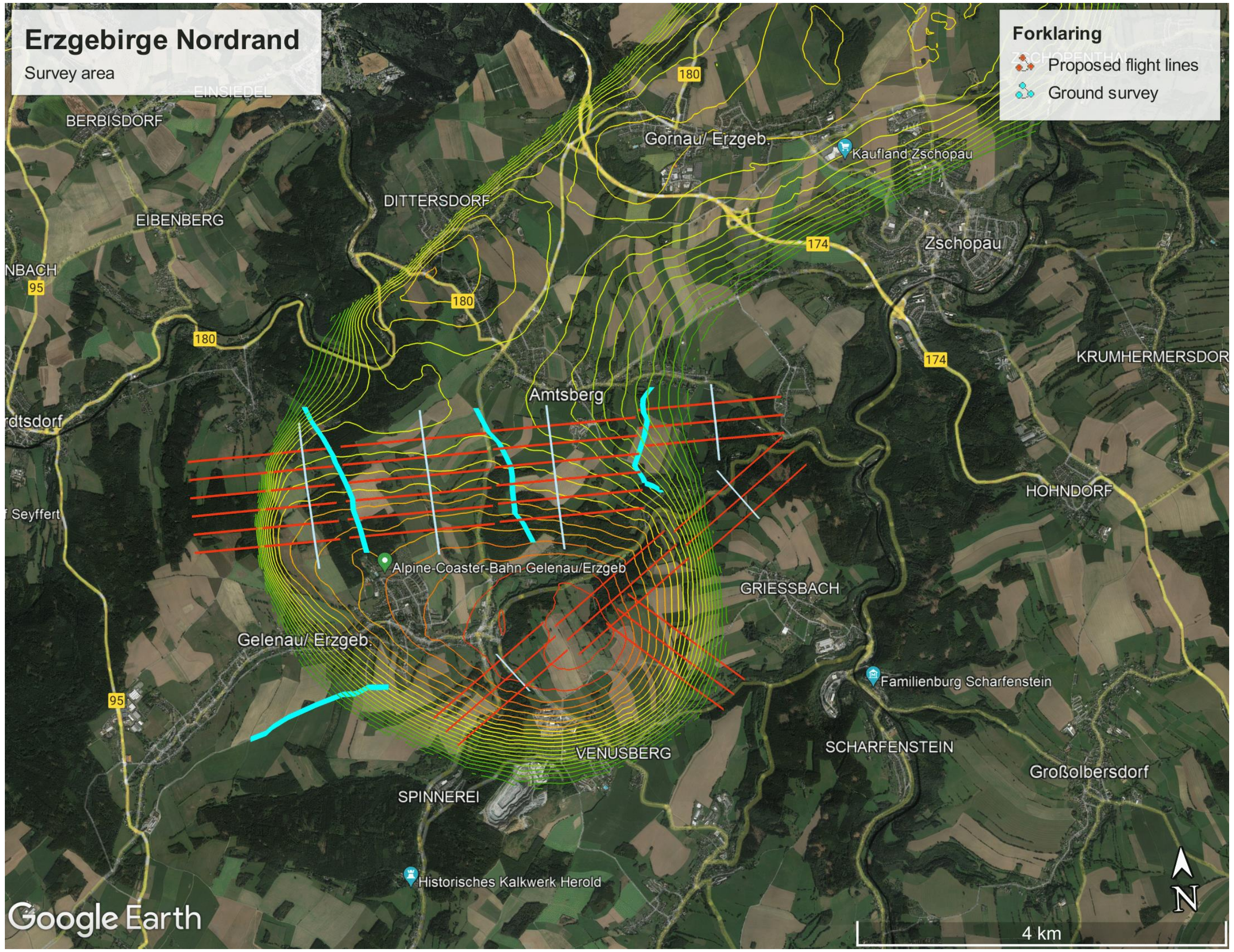
The "Erzgebirge Nordrand" Test

- The Arcsky X55 should arrive with Drone System in week 44 (this week)

- The iMAR IMU is in Germany for an upgrade
  The internal GNSS receiver is getting upgraded – then we do not need an external GNSS receiver

- Together with BEAK and Drone Systems:
  - Areas of interest have been identified
  - Flight lines have been proposed
  - Gound gravity survey has been carried out (we needed an indication of target resolution for setting flight speed)

- Final field plan is awaiting drone testing

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