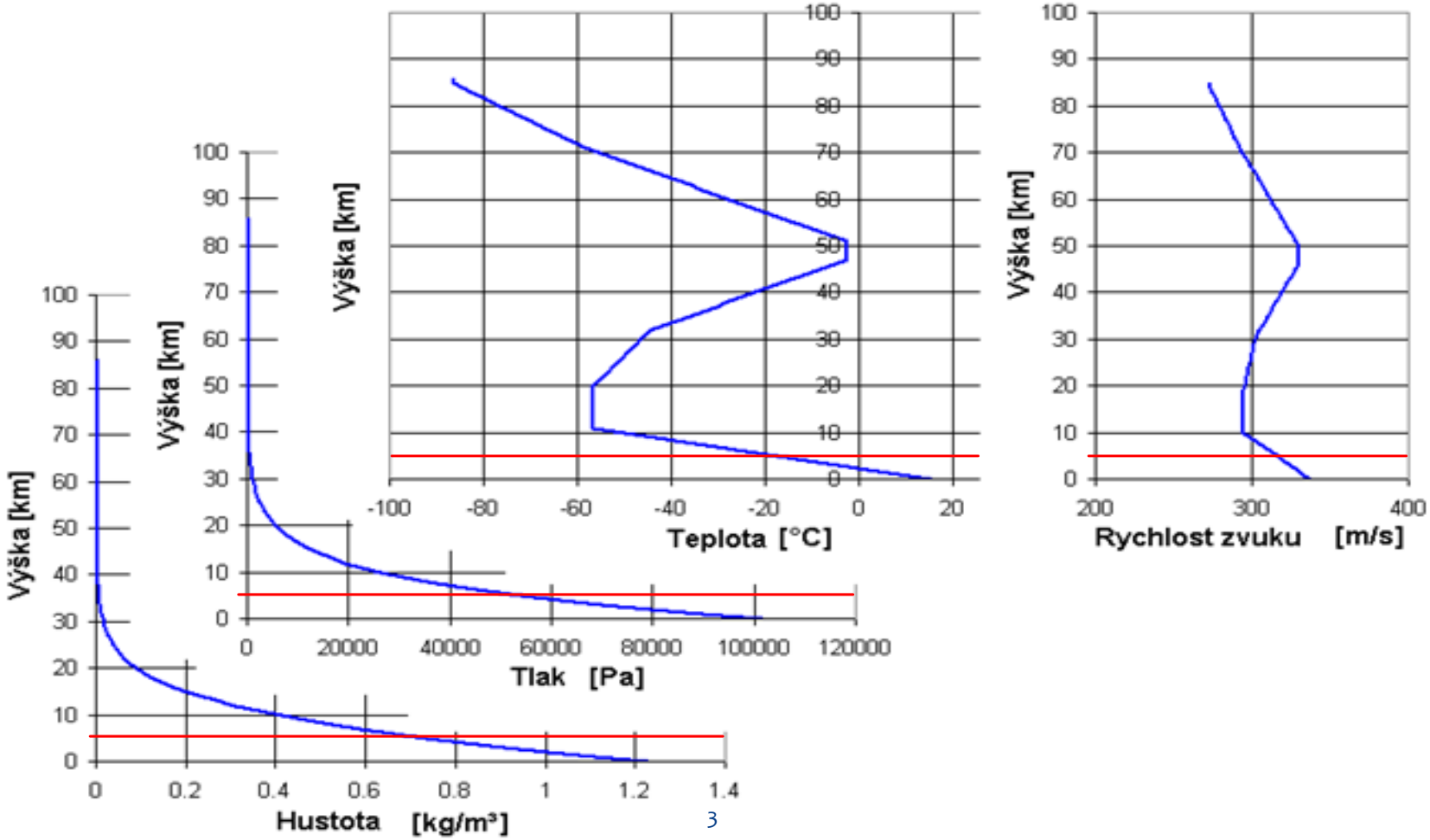
Senzory a akční členy

Pavel Pačes

Obsah

* Senzory používané pro určení orientace a navigaci
* Ilustrace funkce zpracování dat pomocí inerciální měřicí jednotky
* Akční členy používané pro dosažení požadované polohy
* Ilustrace stabilizace kosmických prostředků s pomocí modelu malého satelitu
* Navigační algoritmy a jejich slabiny
* Informace o výuce principů senzorů, metod měření a zpracování dat na ČVUT FEL.

Mezinárodní standardní atmosféra



```
cd d:\Projects\prjCAN_Tbx\srcCanTbx_v16
CANTBX_InstallToolbox
CANTBX_InitTxb
addpath d:\Projects\prjSmallSatPlatform\05_SSP_IO\
cd d:\Projects\prjSmallSatPlatform\05_SSP_IO\
addpath
d:\Projects\GrantGR_2011_13_TACR_Safety\Vysledky\V008_Sonda\Sond
a\ProbeIO\
SSP_OpenTCP(0, 5 )
PIO_OpenTCP(1, 15)
```

Test

* Jak se mění tlak s výškou?

* Absolutní senzor tlaku.
  * Existuje absolutní způsob měření?

[iRetVal fPress fTemp] = SSP_Read_PaT(0)

PIO_Maintenance_AskStaticPressure(1)
[iRetVal fPressure_mBar oData] = PIO_PressureStatic_Get(1)

Zpřesňování informace

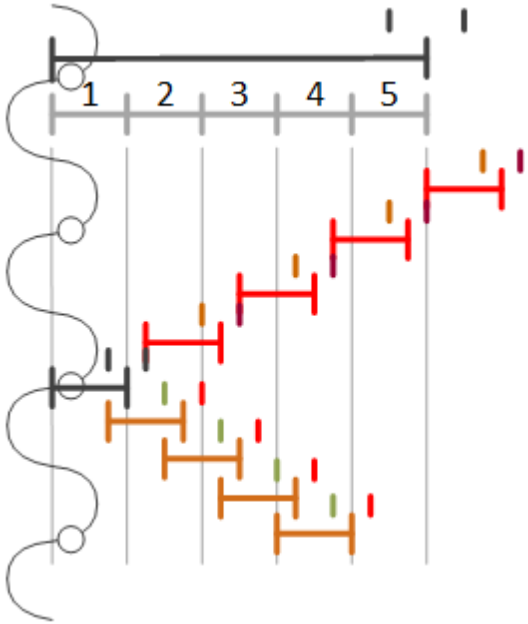
cd d:\Projects\prjSmallSatPlatform\10_Tasks\01a_Intro_and_Pressure\00_Matlab\

SSP_T01_Pressure – two positions

SSP_T02_3DboxPio – ilustrate movements with two boxes

Senzor

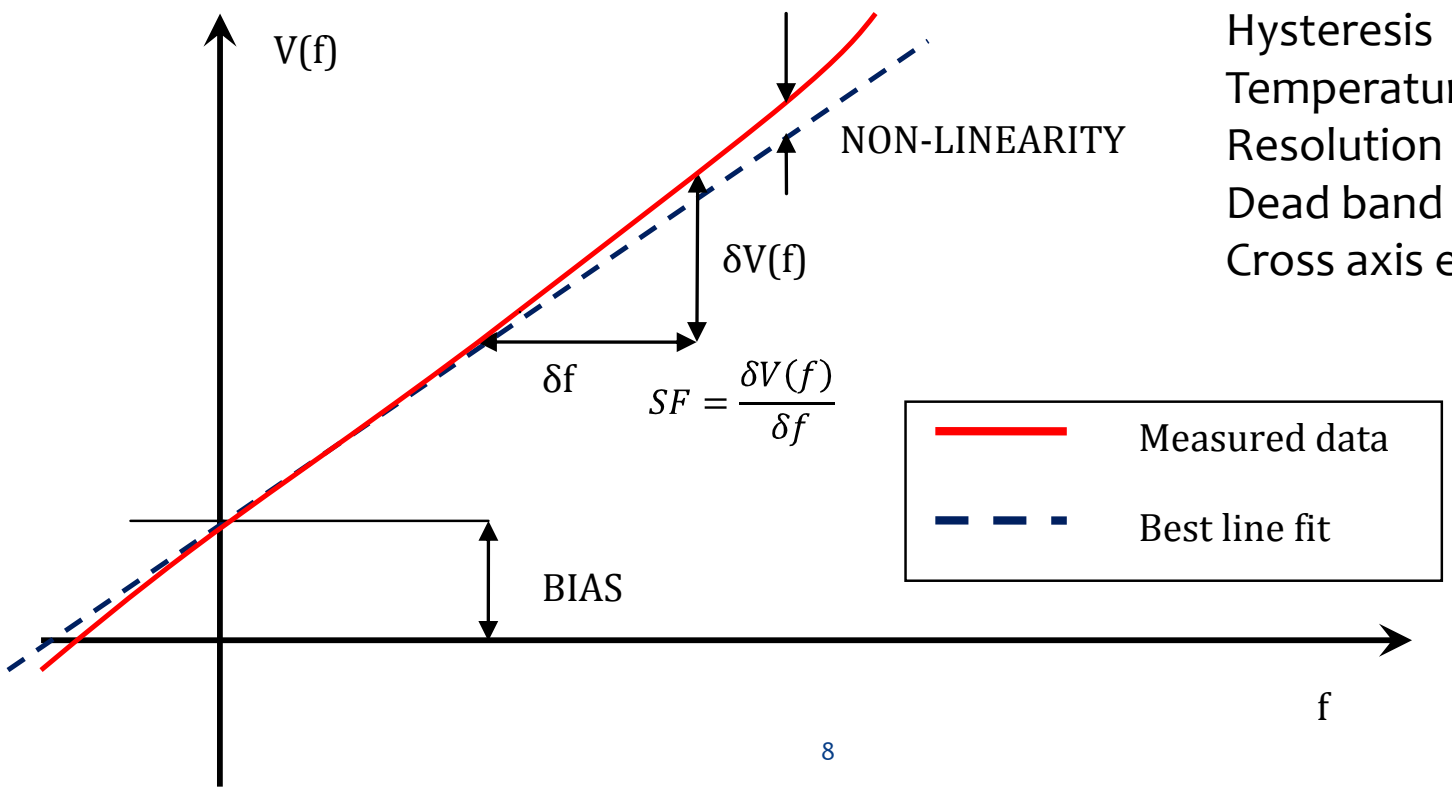
* Převod některého ze základních fyzikálních principů na elektrický signál



Přesnost měření/princip

* Absolutní
* Relativní

Výstup senzoru

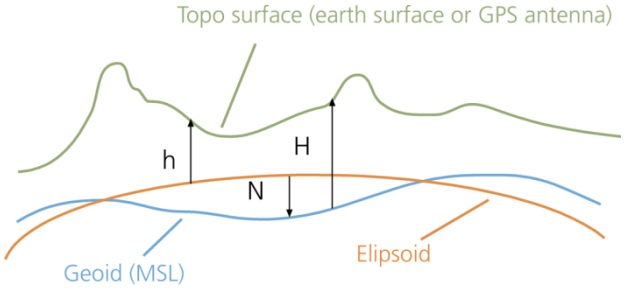


Linearity error
(Scale factor)
Bias
Hysteresis
Temperature effects
Resolution
Dead band
Cross axis effects

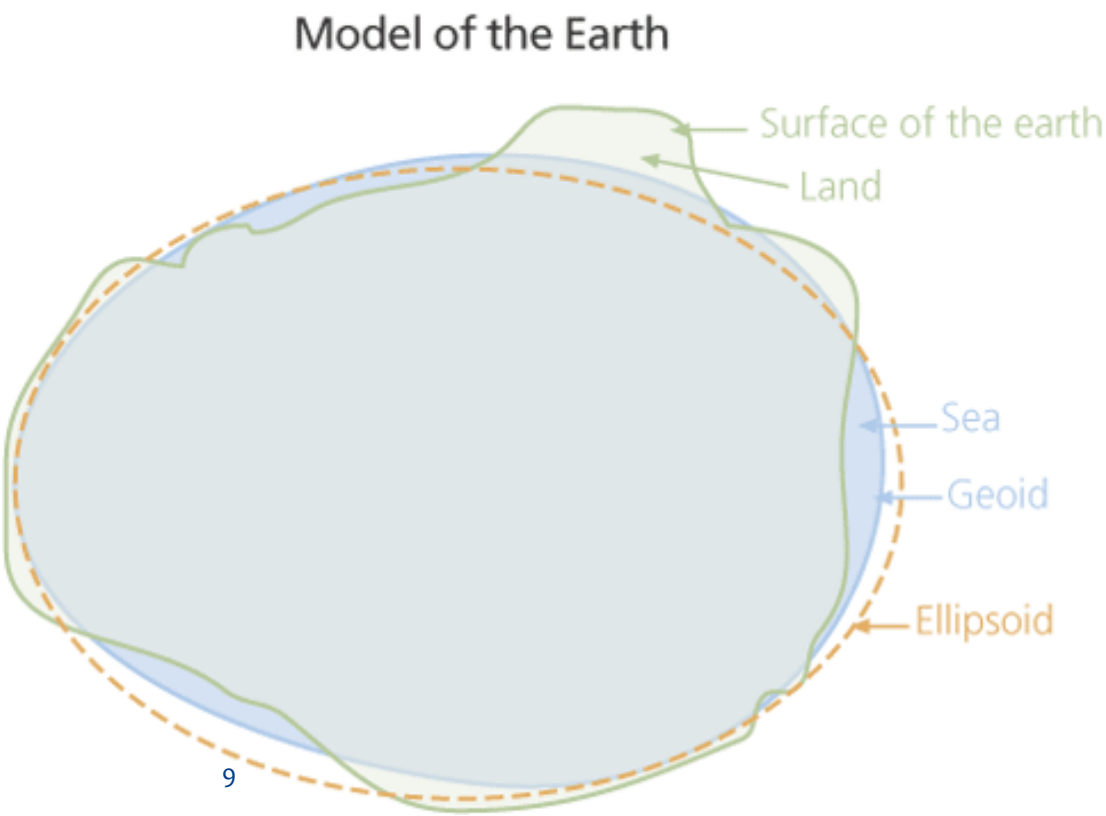
Země

* Povrch
* WGS84
* Geoid?

h=H+N



h=elipsoid height
H=orthometric height
N=geoid height



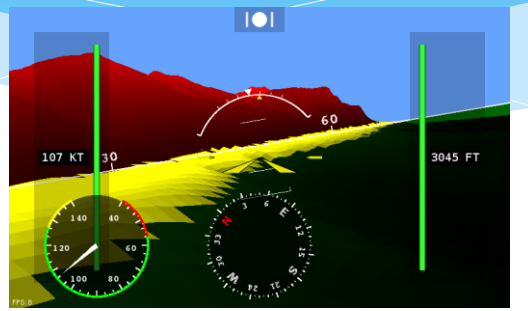
Povrch - SRTM

* NASA JPL, NGA
* Raketoplnán Endeavour (2000)
  * 11 dnů
* Měření odrazů rádiových vln
* Různá rozlišení
  * 1” (30 m) USA, Australia
  * 3” (90 m) Svět
* ~ 750 000 uživatelů

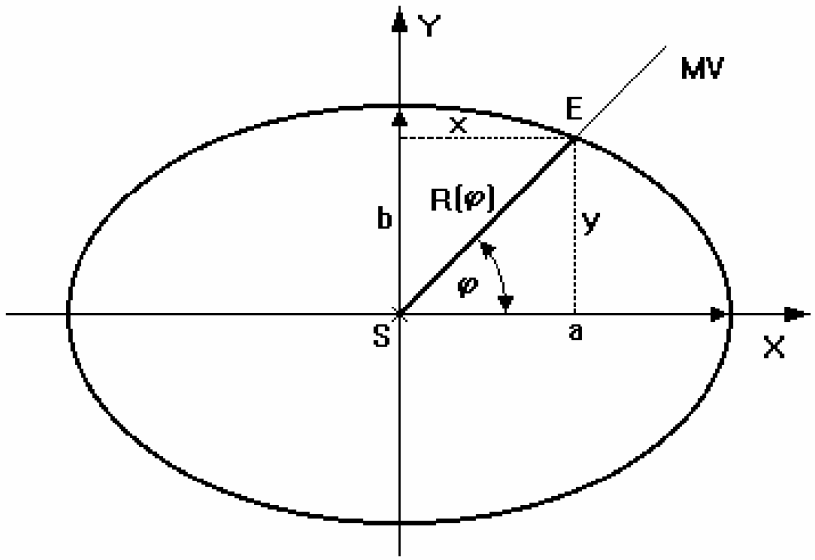
Využití

* Topografické podklady
  * Mapy
  * Hry
  * Simulace (povodně)
  * Navigace

* Video



WGS84



* Earth is not a sphere
  * It is described as rotational ellipsoid
  * International Ellipsoid

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1$$

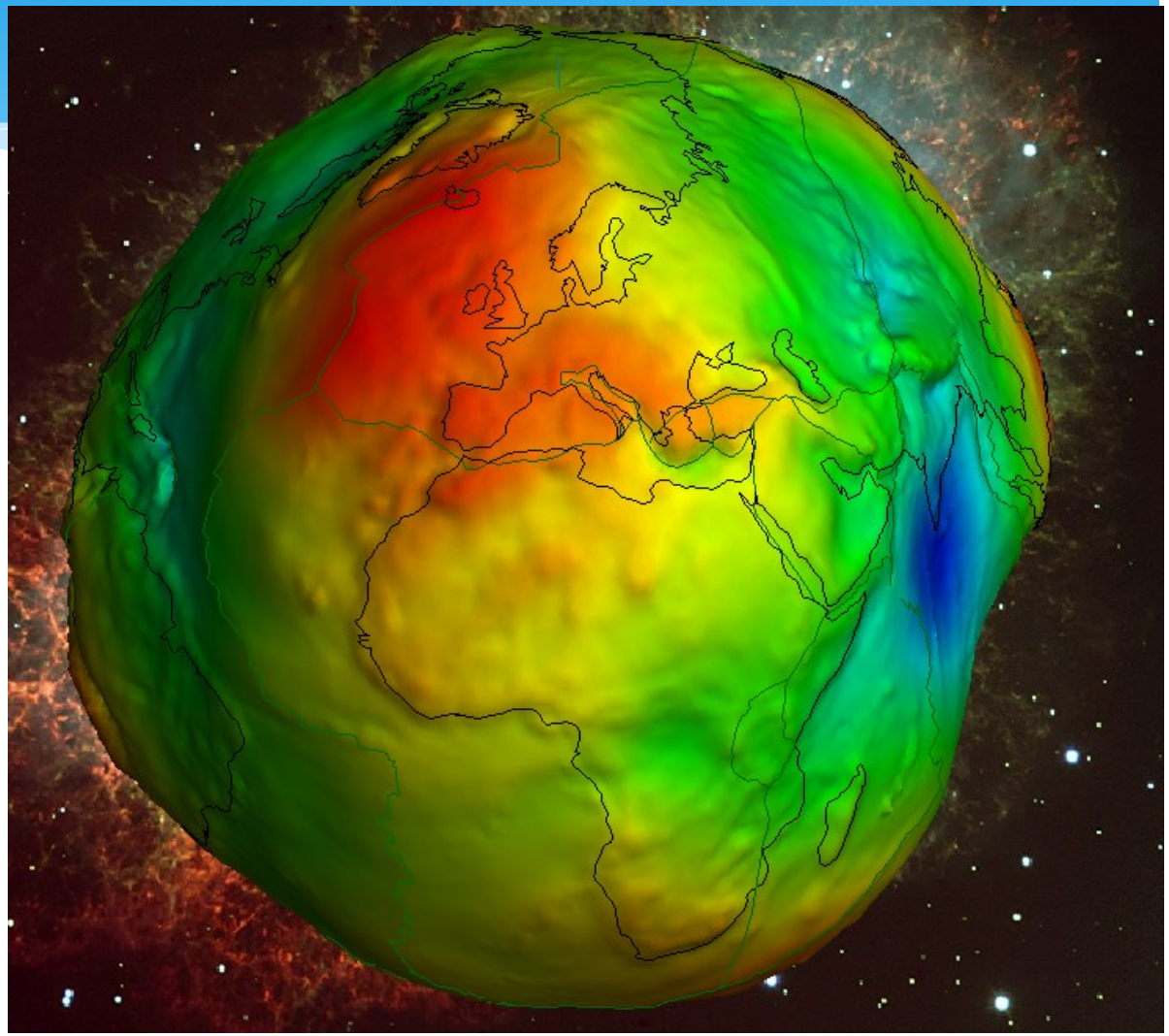
$$x = R(\varphi)\cdot\cos\varphi$$

$$y = R(\varphi)\cdot\sin\varphi$$

$$R(\varphi) = \frac{a\cdot b}{\sqrt{b^2\cdot\cos^2\varphi + a^2\cdot\sin^2\varphi}}$$

a=	6378 160 m
b=	6356 774,5161 m
a-b=	21385,483 9 m
i=(a-b)/a=	0,003352 923711
$e^2=(a^2 - b^2)/a^2=$	0,00669460532856
$e'^2=(a^2 - b^2)/b^2=$	0,00673972512832
e=	0,08182056788
$c=a^2/b=$	6399617,4290 m
obvod rovníku=	40075161,1992 m

Geoid



http://icgem.gfz-potsdam.de/ICGEM/

Gravitační pole

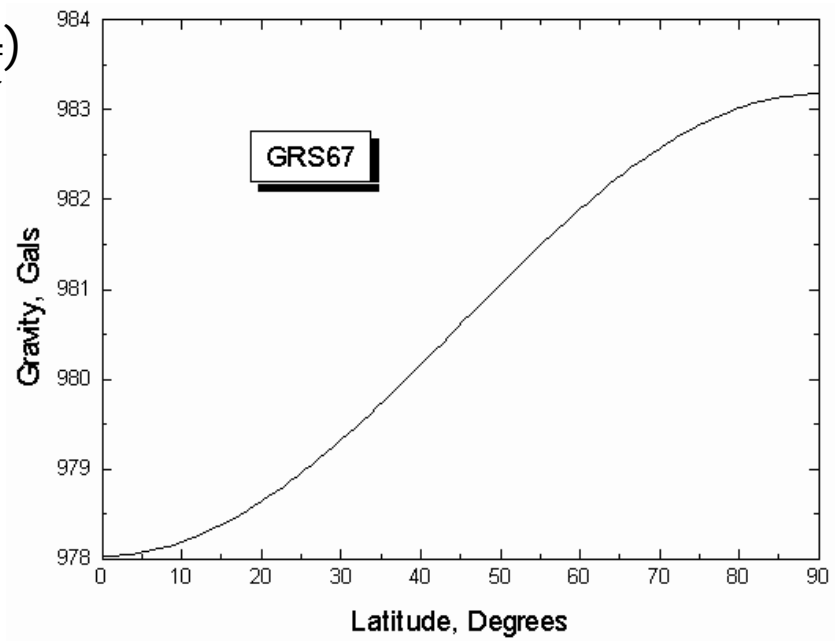
* Formed in 1980 and used in WGS84 model
  * After some errors were found in the previous models

$$g_0 = 9.7803267714 \left(\frac{1+0.00193185138639 sin^2\lambda}{\sqrt{1-0.00669437999013 sin^2\lambda}}\right)$$

Gravity anomaly

* 1 Gal = 1 cm/s²
* 1 Gal = 0.01 m/s²

Diff. from the top of Mount Everest to sea level ≈ 2 Gal (0.02 m/s2)

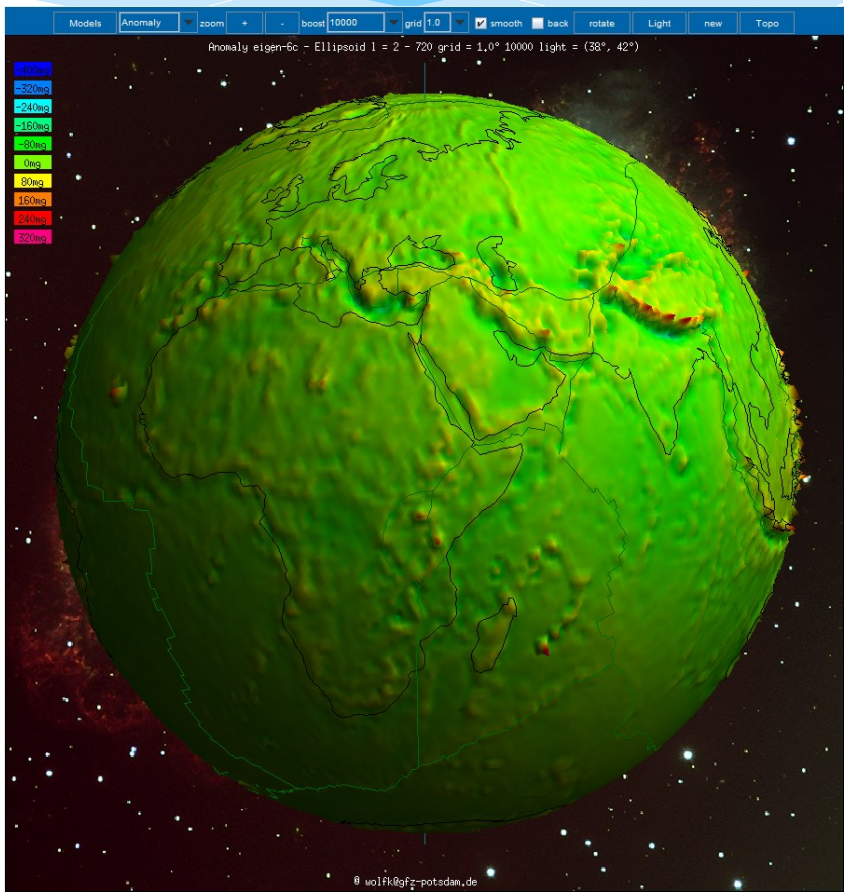


Gravitační pole

- Gravity dependence on altitude
  - h height above the Earth's surface
  - g_0 gravitational acceleration on the surface
  - r_e radius of the Earth

$$g_h = g_0 \left(\frac{r_e}{r_e + h} \right)^2$$

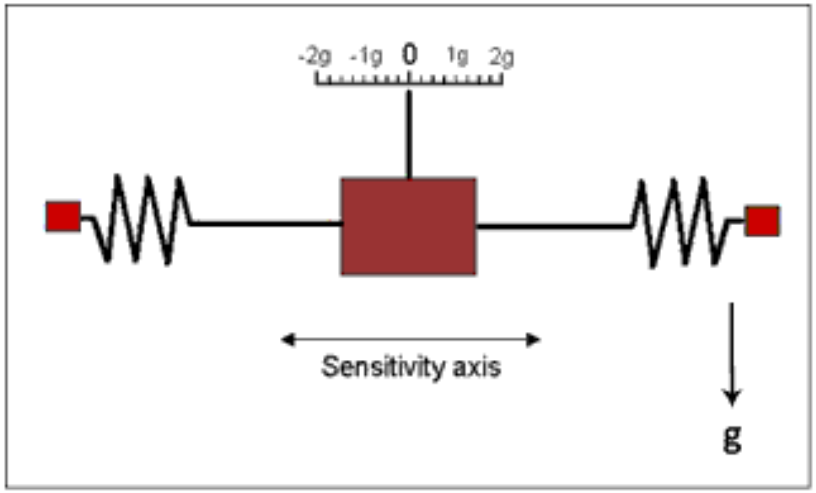
- Local topography dependence
  - Anomalies – mountains, under sea
  - **Density of the material**

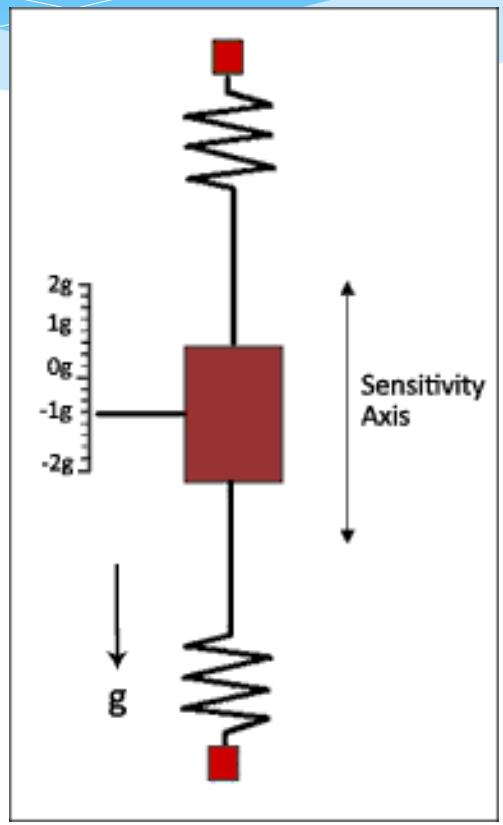


Sensors

* Mass accelerometers
  * m = proof mass,
    moving in specified direction

$$F = ma \rightarrow a = F/m$$





CZ

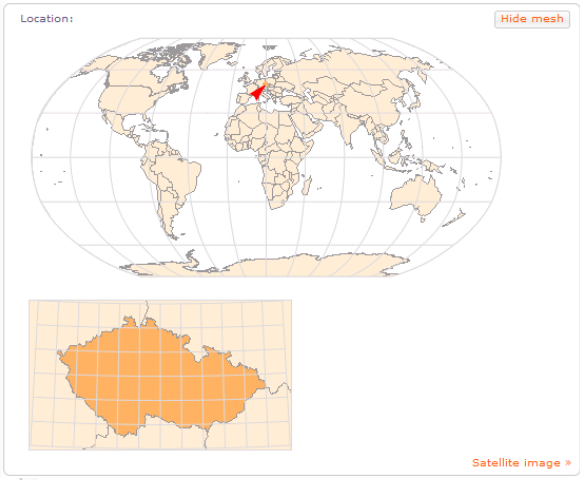
Input interpretation:

gravitational acceleration	Czech Republic

Gravitational field strength for Czech Republic: Show non-metric units

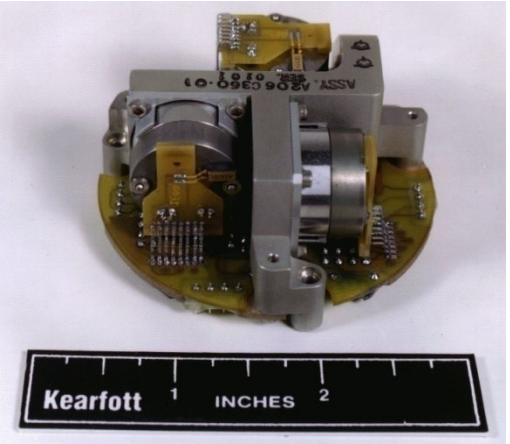
total field	9.81254 m/s^2 (meters per second squared)
angular deviation from local vertical	0.00331° (degrees)
down component	9.81249 m/s^2 (meters per second squared)
west component	4.3×10^{-4} m/s^2 (meters per second squared)
south component	0.03252 m/s^2 (meters per second squared)

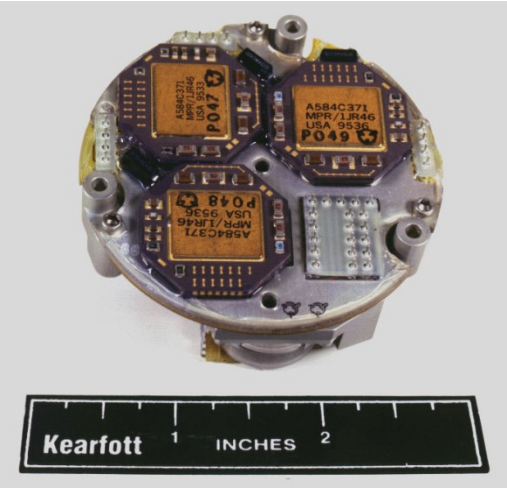
(based on EGM2008 12th order model; 488 meters above sea level)



Accelerometers

Source: Allied Signal and Kearfott



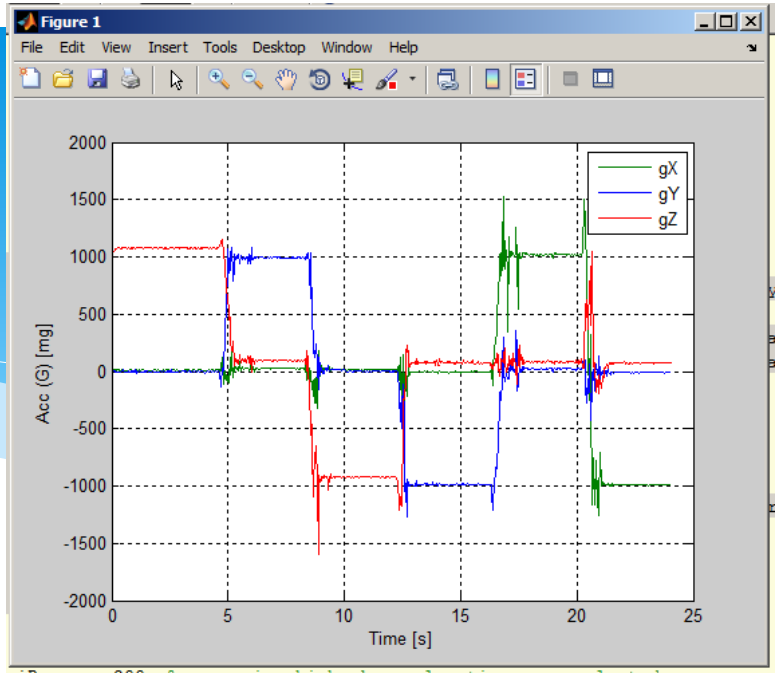


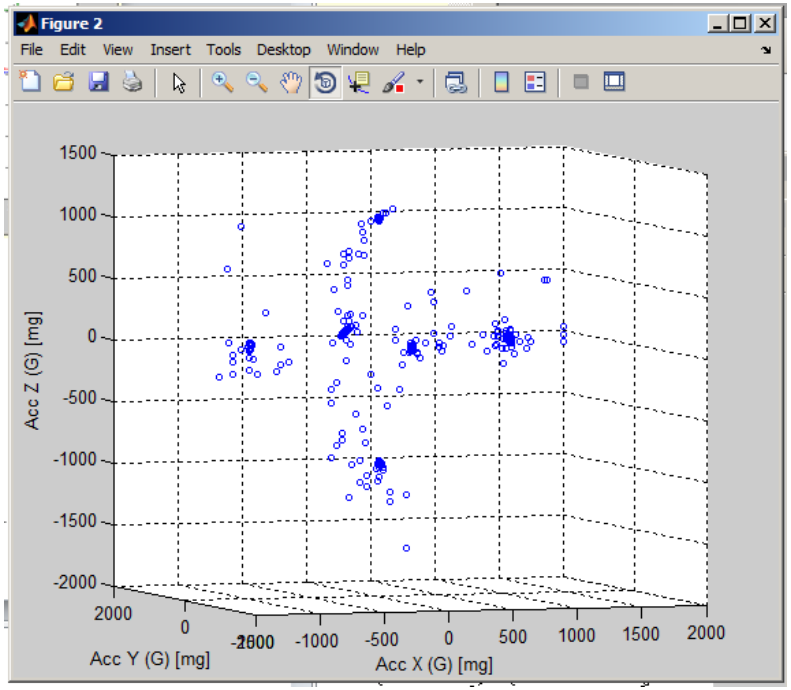
TYPICAL SYSTEM SPECIFICATIONS		
Parameter	**Unit**	**Performance**
Range		
Continuous	*g*	0 ±60
Intermittent	*g*	0 ±100
Scale Factor		
Absolute	mA/*g*	1.20 ±15%
Thermal Model	ppm	100*
Stability 1 Year	ppm	100
Bias		
Absolute	mg	0 ±100
Thermal Model	µ*g*	85*
Stability 1 Year	µ*g*	100
Misalignment		
Absolute	mrad	0 ±20
Thermal Model	µr	35*
Stability 1 Year	µr	50
Temperature Sensor	µA/°C	1.0
Threshold	µ*g*	<1
Linearity	µ*g*/*g*^{2}	0 ±5
Cross Coupling	µ*g*/*g*^{2}	0 ±5
Vibration Rectification	µ*g*/*g*^{2}rms	0 ±10
Vibration	*g*rms	10
Shock	*g*	120
Temperature	°C	-54 to +95
Power	W	2.0
Weight	gm	160

Test

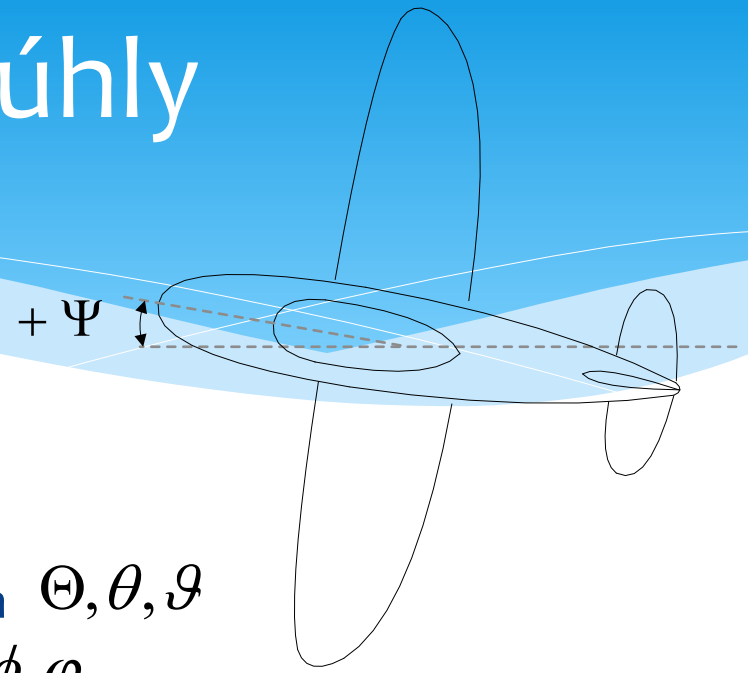
* Kalibrace senzoru
* y = *a**x+*b*

* SSP_T05_2_Acc_Calibration

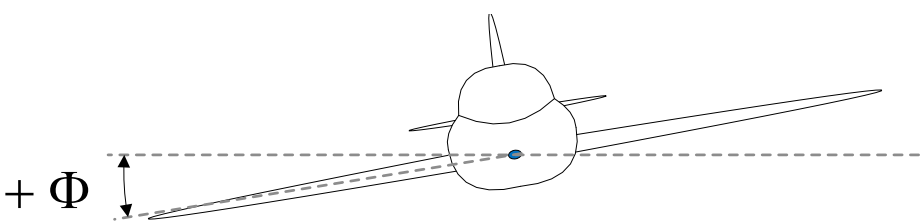


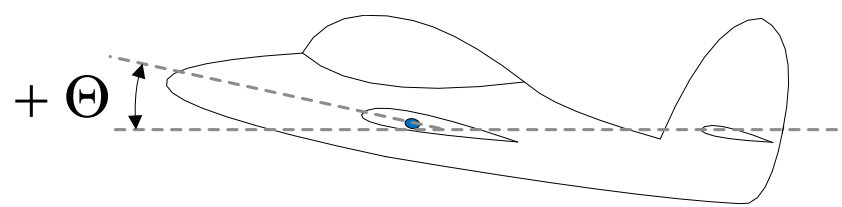


Polohové úhly

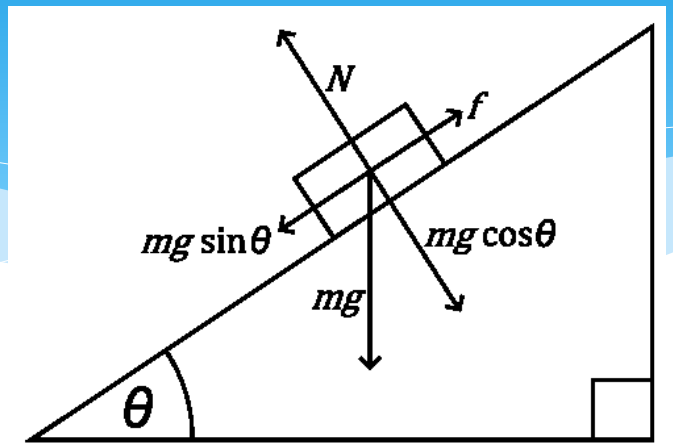


- Axes conventions
  - Position angles
    - Theta Θ, θ, pitch – podélný sklon $\Theta, \theta, \vartheta$
    - Phi Φ, φ, roll – příčný náklon Φ, ϕ, φ
    - Psi Ψ, ψ, yaw, heading, azimuth – kurz Ψ, ψ
  - Body frame – connected to the airplane
  - Navigation frame – what is the reference for this?





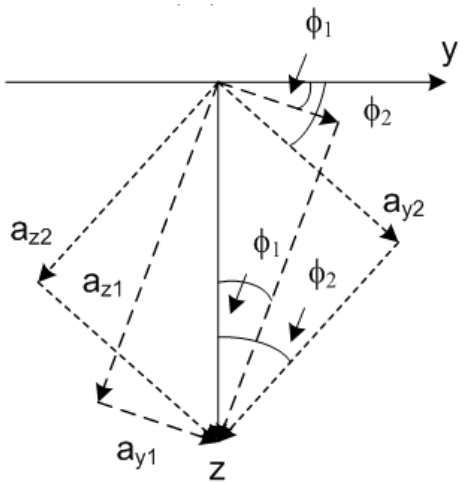
Task - Inclined plane



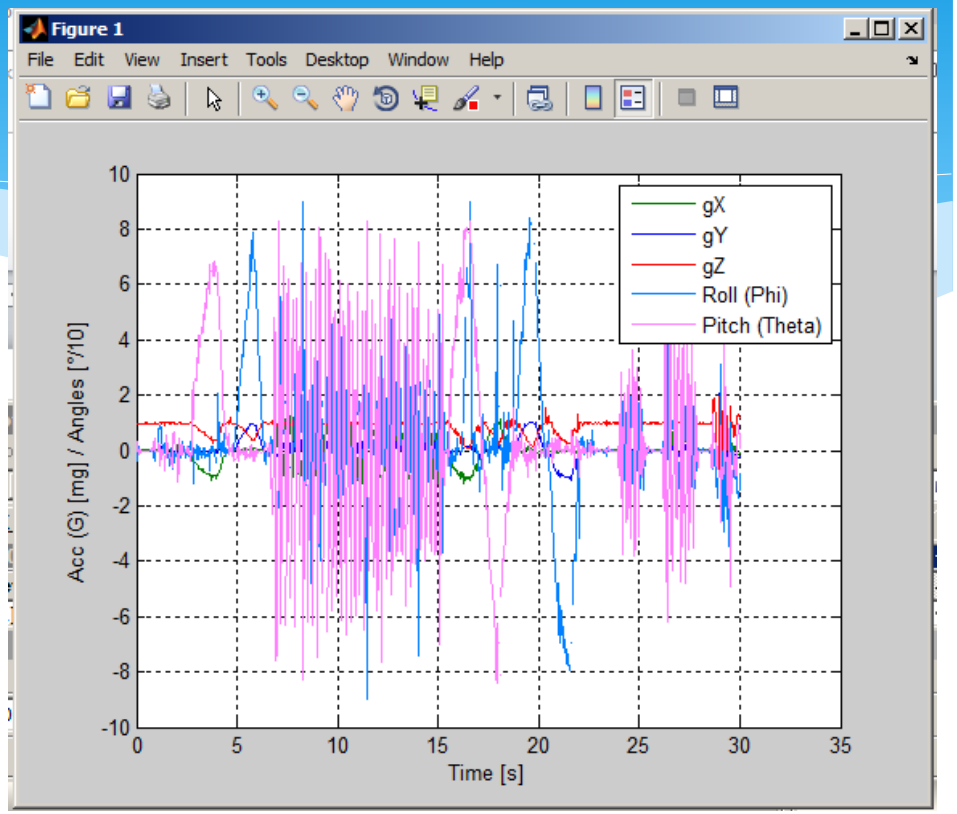
- Where is pitch, roll and yaw?
- Where are the body and navigation frames?

$$\Phi = sign\left(f_z\right)\arcsin\left(\frac{f_y}{g}\right)$$

$$\Theta = -sign\left(f_z\right)\arcsin\left(\frac{f_x}{g}\right)$$

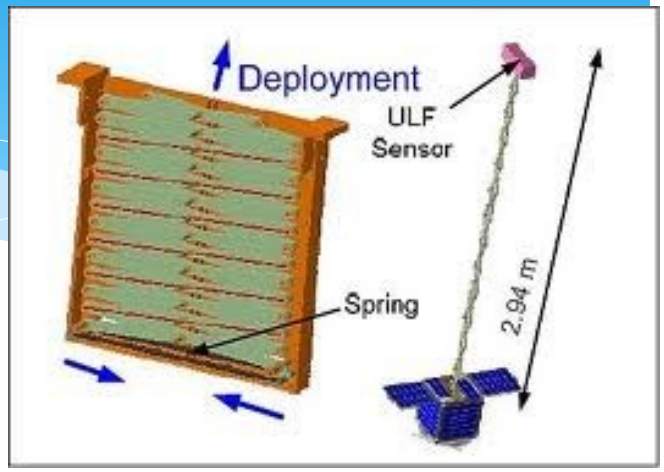


Test



* Vliv zrychlení na určení polohových úhlů
  * Výpadky v grafu
  * Jak se chová Gx, Gy, Gz
  * Co na to Roll a Pitch
* SSP_T05_3_Acc_PositionAngles

Space



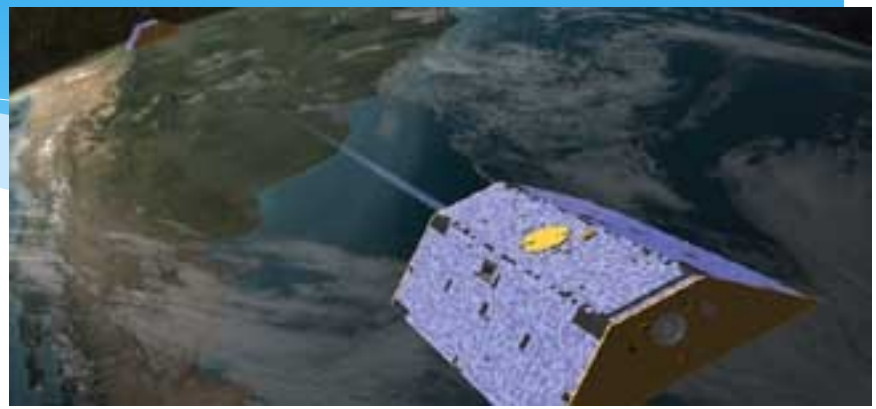
Escape velocity

* V1 = keep circular orbit
* V2 = leave the gravitational field of Earth
* V3 = leave our Solar system

Gravitational stabilization with a boom

* Simple, reliable, no power demands
* Occupy space

Gravitational Field Measurement



GRACE experiment

* Gravity Recovery and Climate Experiment
* Two satellites
* Flying in a formation
* The distance between them is measured by a microwave radar and transferred to the second device
* While a satellite pass over a region with higher gravity its speed increase (it is pulled forward)
  – e.g. The distance between satellites shortens

Credit: University of Texas

Angular speed

- Course alignment
  - Measurement of Earth rotation vector projected at local latitude

$$\left|\vec{\Omega}_Z\right| = 7,292115 \cdot 10^{-5} rad \cdot s^{-1}$$

  - We can use angular rate sensors in body frame where

$$\Omega_Z = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2}$$

$$\mathbf{C}_n^b = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \cdot \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}$$

  - We know Θ and Φ =>

$$\omega_n = \left(\mathbf{C}_n^b\right)^{-1} \omega_b = \begin{bmatrix} \omega_{nx} \\ \omega_{ny} \\ \omega_{nz} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\phi\sin\theta & \cos\phi\sin\theta \\ 0 & \cos\phi & \sin\phi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \cdot \begin{bmatrix} \omega_{bx} \\ \omega_{by} \\ \omega_{bz} \end{bmatrix}$$

  - **Do we know where we are?**

CZ.1.07/2.3.00/35.0029

Angular speed

* Vertical component of the Earths rotation
  * $\omega_{nz} = -\Omega_Z \cdot \sin\varphi$
    * $\omega_{nz} < 0$ North hemisphere
    * $\omega_{nz} = 0$ Equator
    * $\omega_{nz} > 0$ South hemisphere
  * Course

$$\omega_{nx} = \Omega_Z \cdot \cos\varphi \cdot \cos\psi$$
$$\omega_{ny} = \Omega_Z \cdot \cos\varphi \cdot \sin\psi$$

$$\tan\psi = \frac{\dfrac{\omega_{ny}}{\Omega_Z \cdot \cos\varphi}}{\dfrac{\omega_{nx}}{\Omega_Z \cdot \cos\varphi}} = \frac{\omega_{ny}}{\omega_{nx}} \qquad \psi = \arctan\frac{|\omega_{ny}|}{|\omega_{nx}|}$$

* Any problem?

Gyroscopes

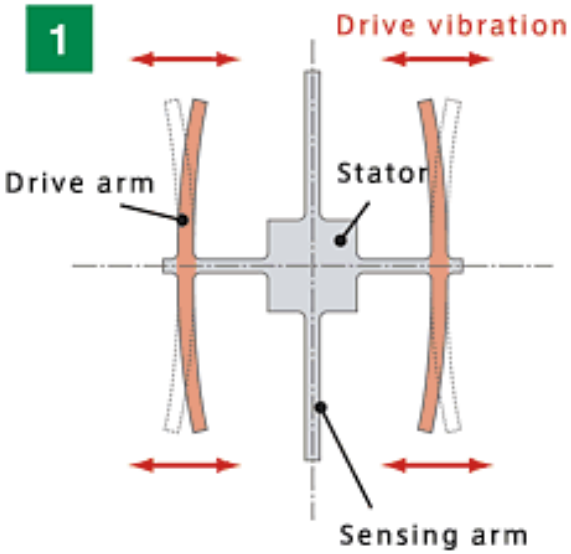
evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

* Coriolis force
  * Oscillating beam experiences in-plane rotation
  * Coriolis force causes perpendicular vibrations

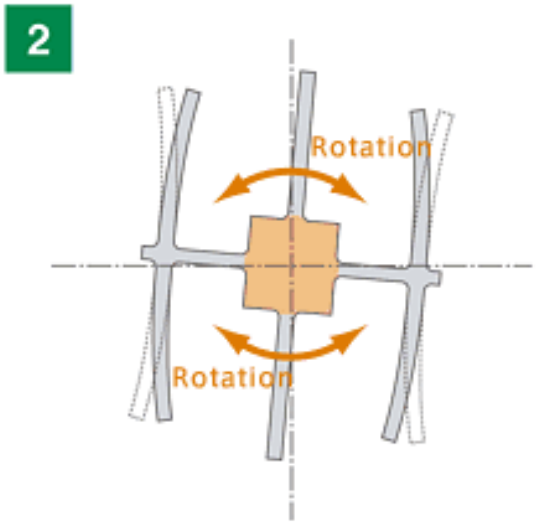
$$\mathbf{F}_C = -2m\mathbf{\Omega} \times \mathbf{v}$$

  * Devices: piezoelectric gyro, hemispherical resonator gyro, MEMS gyro

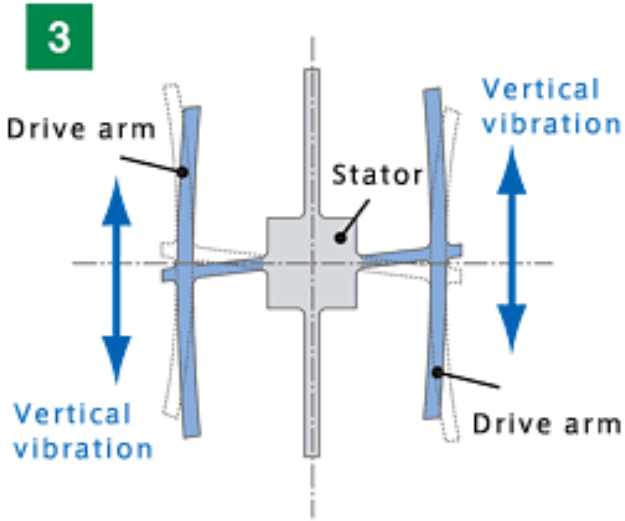
CZ.1.07/2.3.00/35.0029



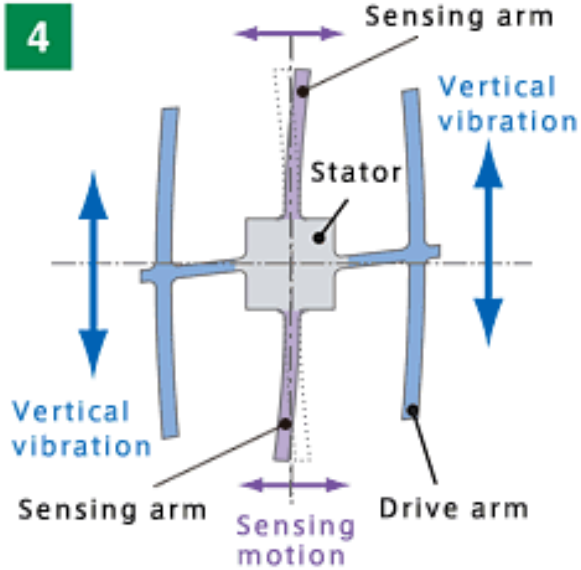
The drive arm oscillates constantly in Drive mode.



Direction of rotation



When the gyro is rotated, the Coriolis force acts on the drive arms, producing vertical vibration.

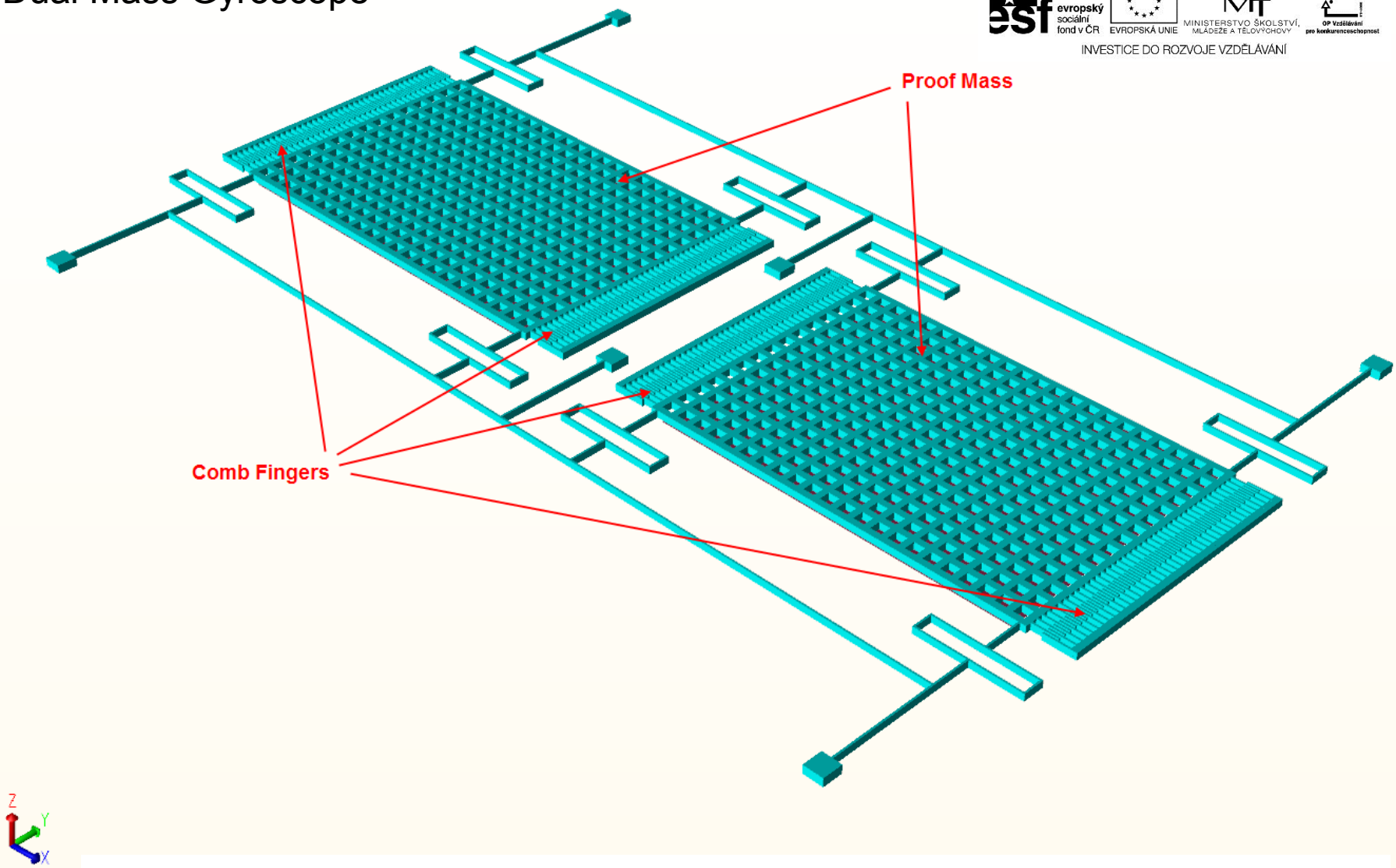


The stationary part bends due to vertical drive arm vibration, producing a sensing motion in the sensing arms.

Source: epsontoyocom.co.jp

CZ.1.07/2.3.00/35.0029

Dual Mass Gyroscope

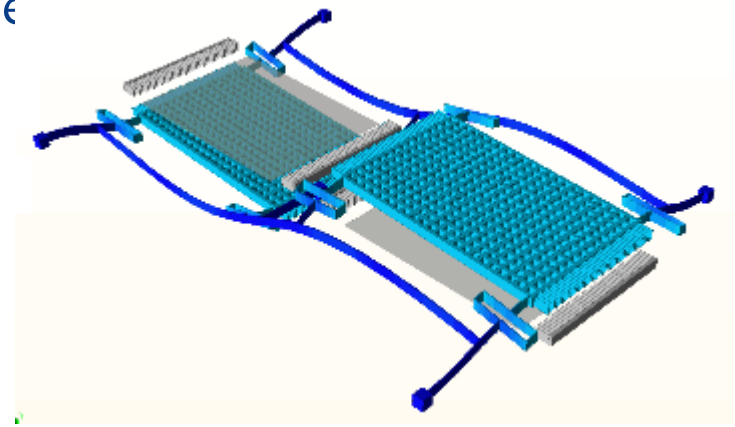


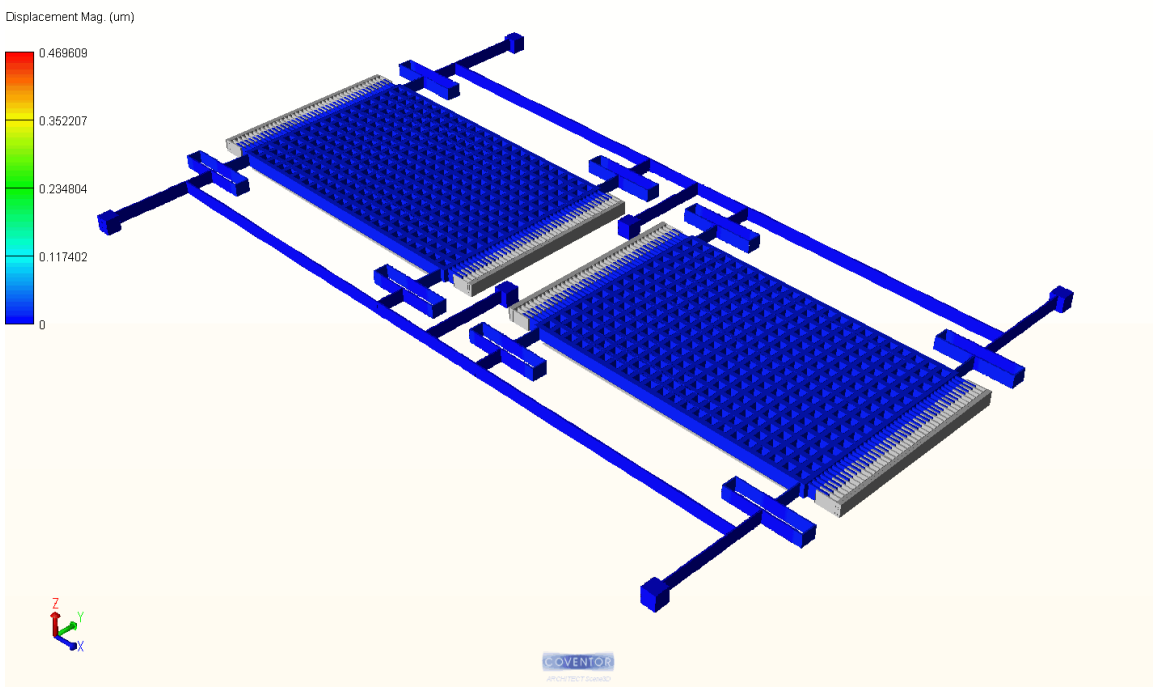
Source: conocimientosrfmemsdesign.blogspot.com

CZ.1.07/2.3.00/35.0029

Dual Mass Gyroscope Video

* Animation of transient simulation.
* For clarity, the fixed electrodes and the comb drives are transparent and the thickness scaled by 2.
* The displacement in Z is also scaled by a factor of 1 000,000 to allow the movement of the gyroscope

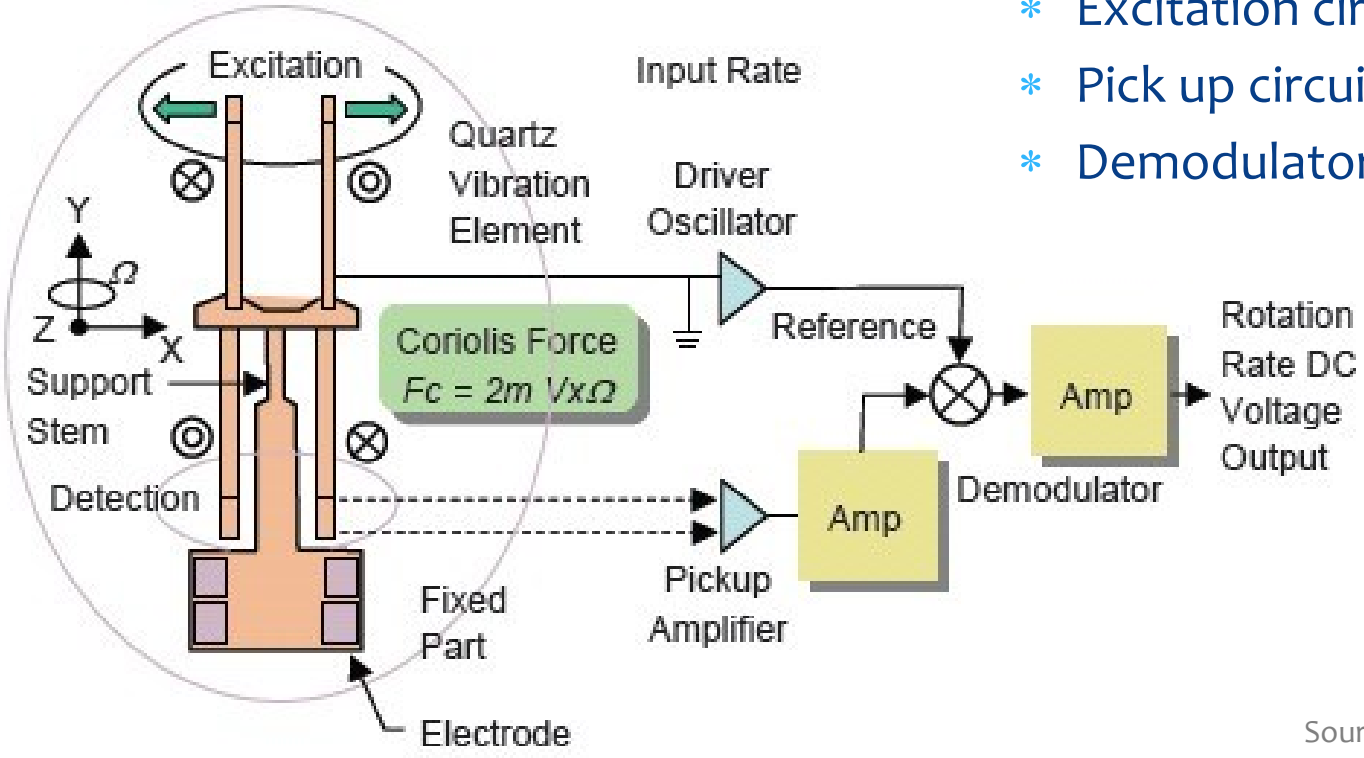



Displacement Mag. (um)
0.469609
0.352207
0.234804
0.117402
0
Z
Y
X
COVENTOR

MEMS Vibrating gyroscope

Coriolis force based sensor is composed from:

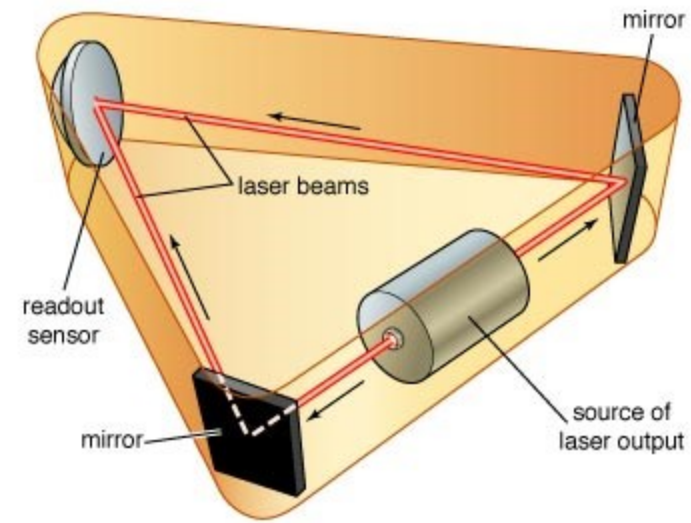
* Vibrating element
* Excitation circuit
* Pick up circuit
* Demodulator



Source: findmems.com

Laser Gyroscope fundamentals

* Light interference
* Laser light is split to travel opposite directions around a circuit
* Rotation -> path length differences
* Devices:
  * **ring laser gyro (RLG),**
  * **fiber optic gyro (FOG)**



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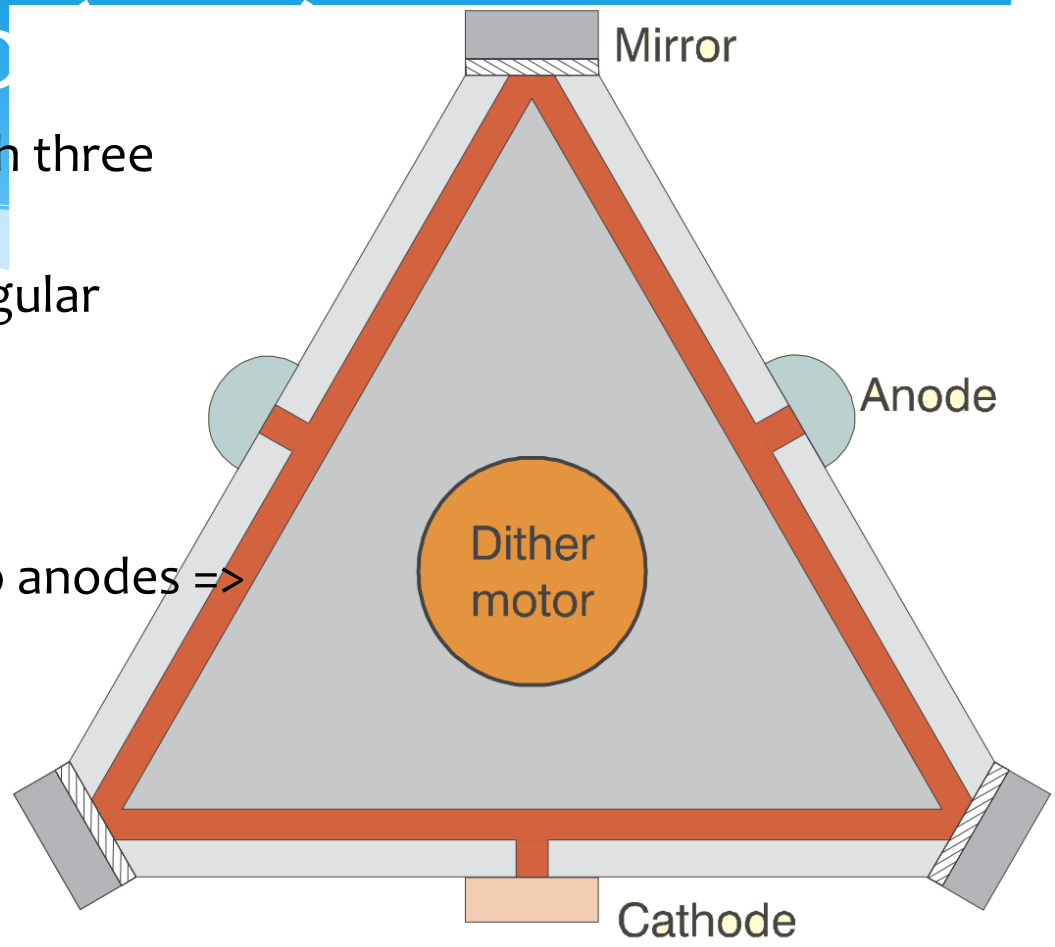
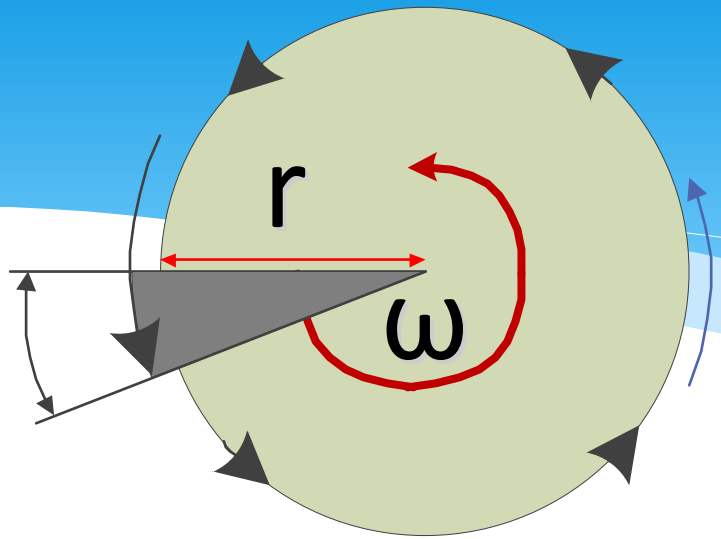
Ring Laser Gyro

- body is a solid glass block, with three narrow tubes drilled in it.
- Mirror at each corner => triangular resonator
- filled with a helium-neon mixture at low pressure
- 1kV between cathode and two anodes => discharge =>
  energy for regenerative lasing action in the gas
- Two lasers
  - a clockwise (CW) beam
  - A counter clockwise (CCW) beam
  - at rest, the two beams have the same frequency (wavelength of 633 nm)



CCW beam

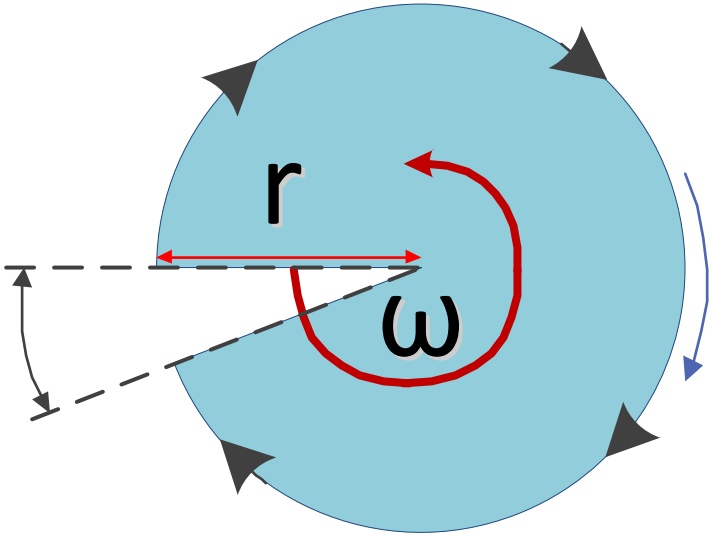
$\Delta L_{+} = V_{co} \cdot T_{+}$



$V_{co} = r \cdot \Omega$

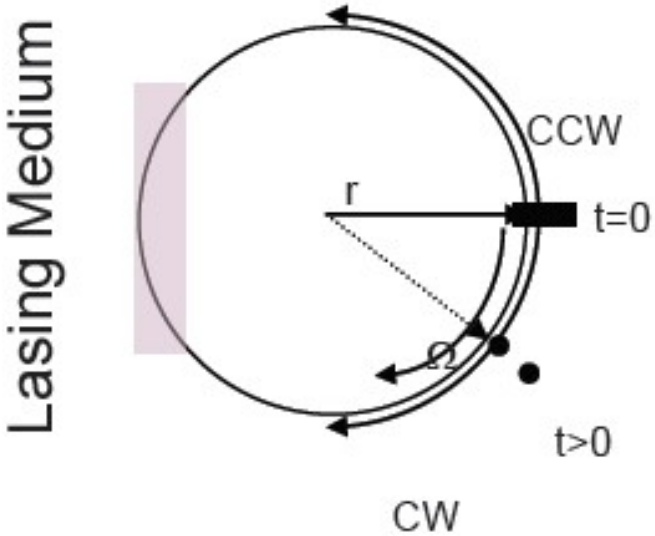
CW beam

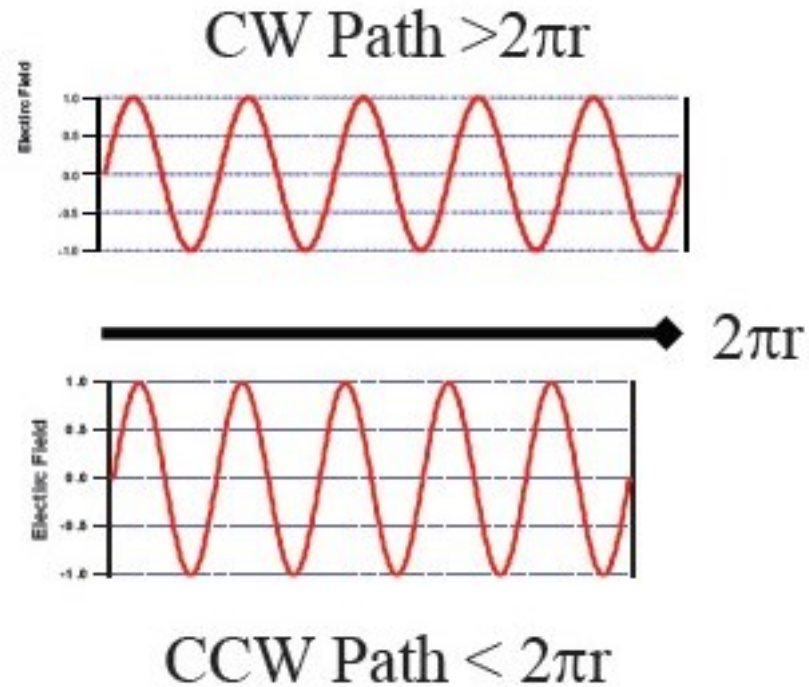
$\Delta L_{-} = V_{co} \cdot T_{-}$



$V_{co} = r \cdot \Omega$

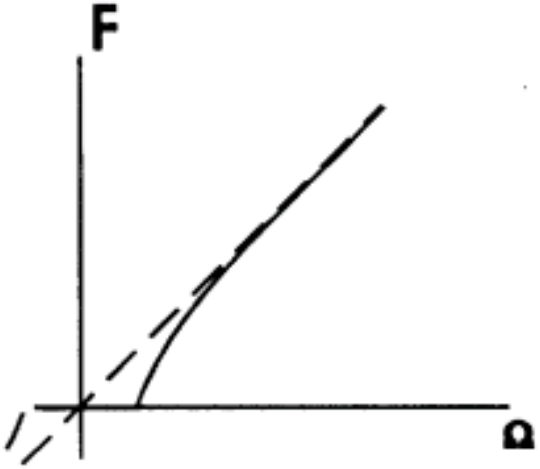
* Sagnac effect manifests itself in a setup called ring interferometry.
* an interference pattern => strips
* Lock-in => dithering

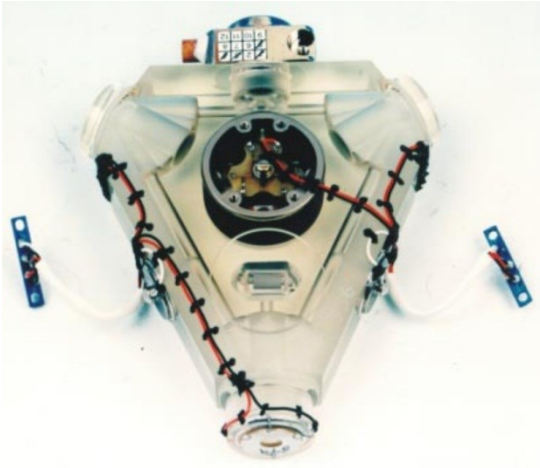


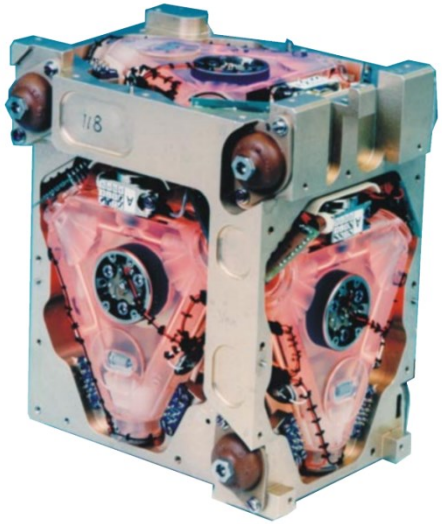


evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

* The difference in path lengths causes a small difference in frequency
* Samples of both beams can be extracted by semi-transparent mirror
* frequency difference => proportional to the applied rotation rate
* Problem => very low rotation rates => mirrors are not perfect => backscatter => lock, or dead band => dither motor - very small rotation (about 1 arc/minute peak, at about 400Hz) to the entire block.

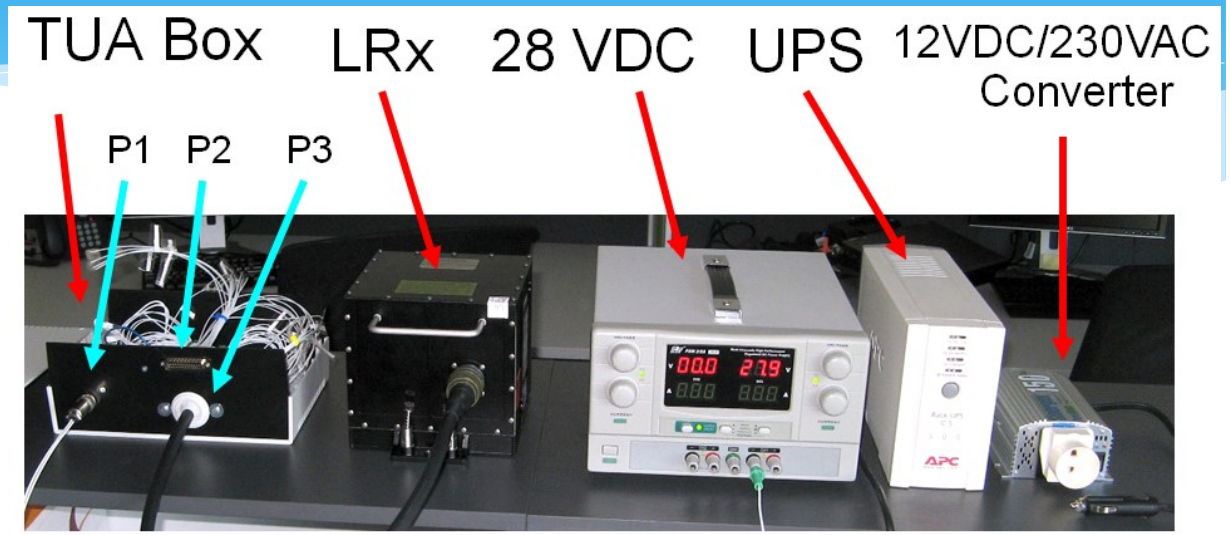






CZ.1.07/2.3.00/35.0029

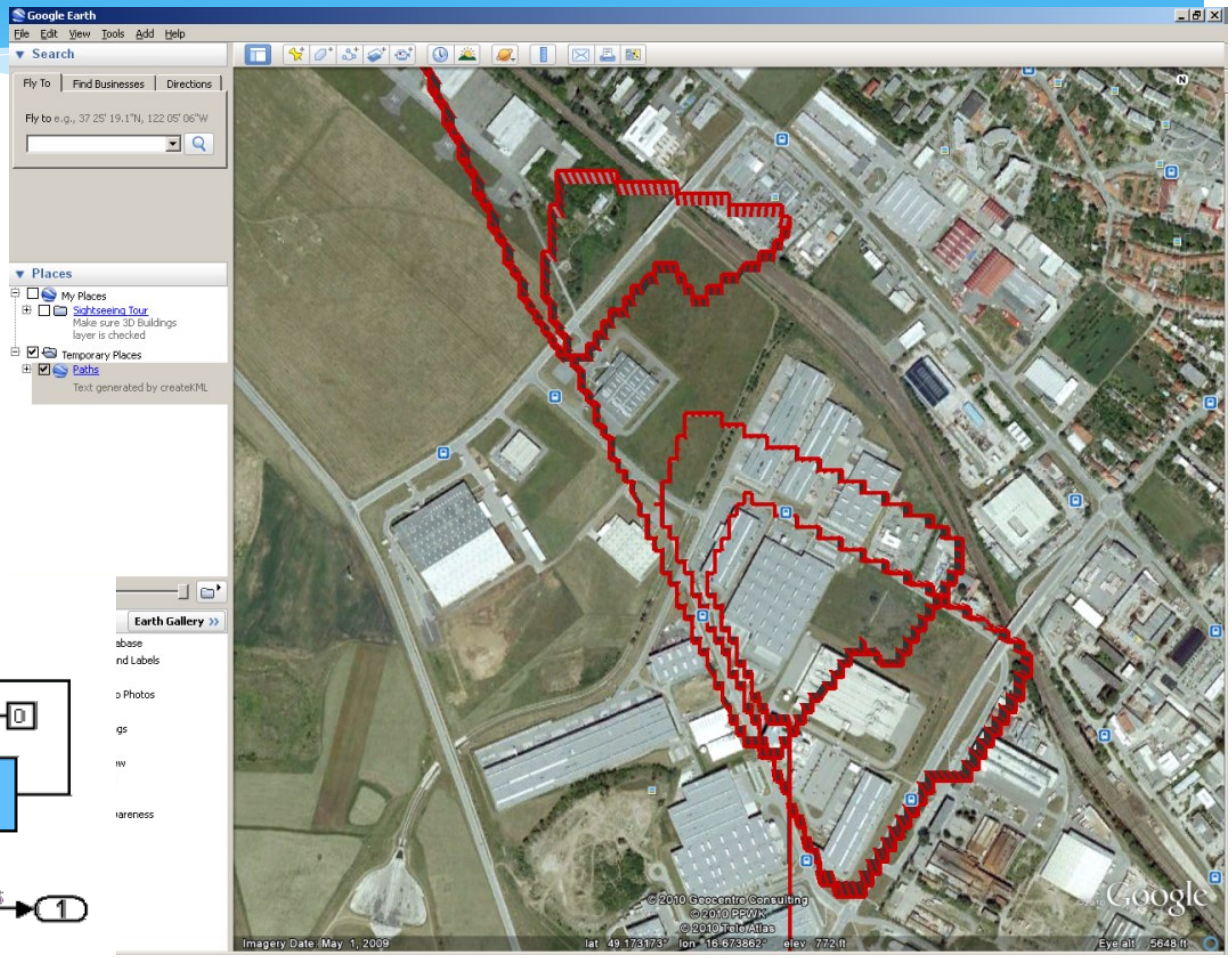
Honeywell Innovators

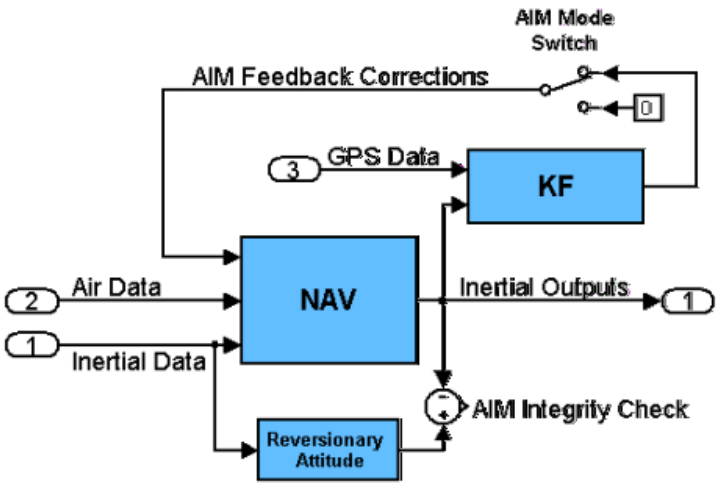


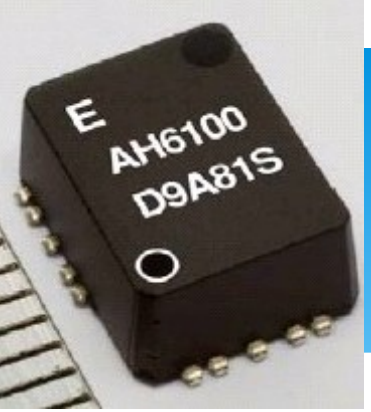
* LaseRefV
* 75000 USD
* RLG sensor
* 118 tis. Kč

Přesnost

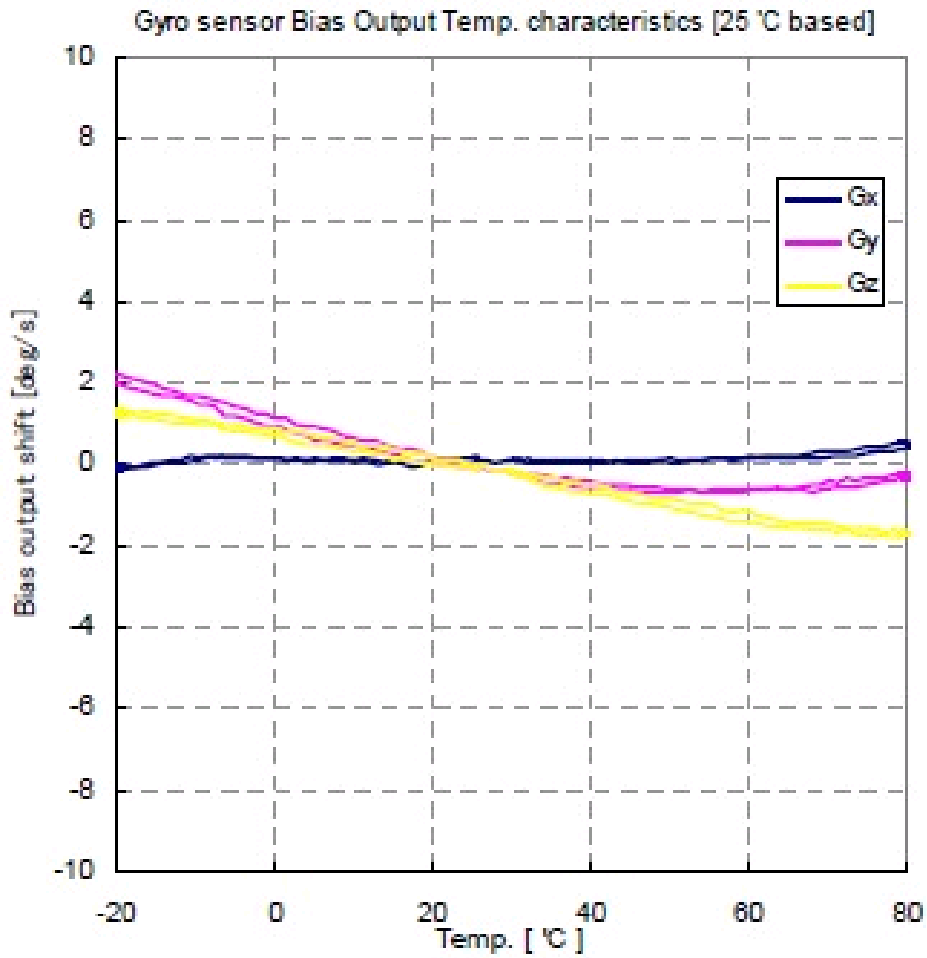
- ARS: RLG
- ACC: Q-Flex quartz
- Jak se na takovou stáž dostat?

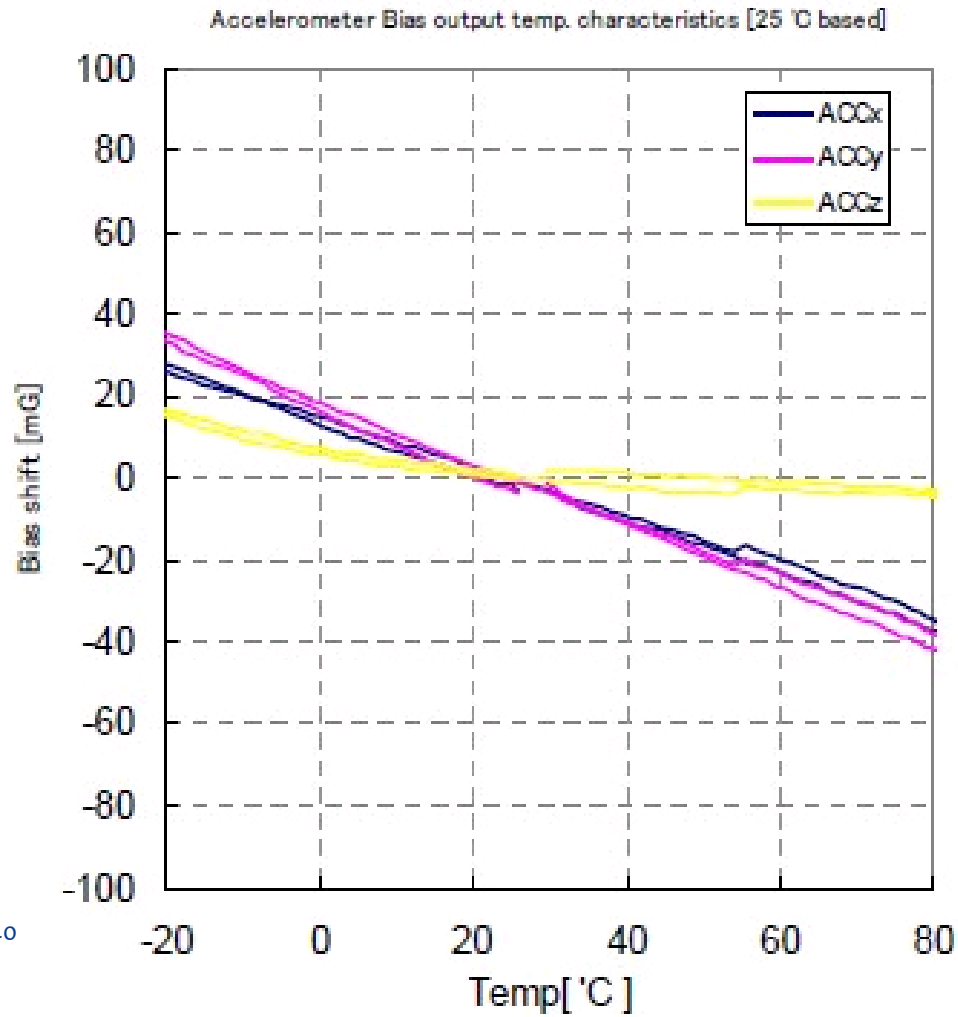






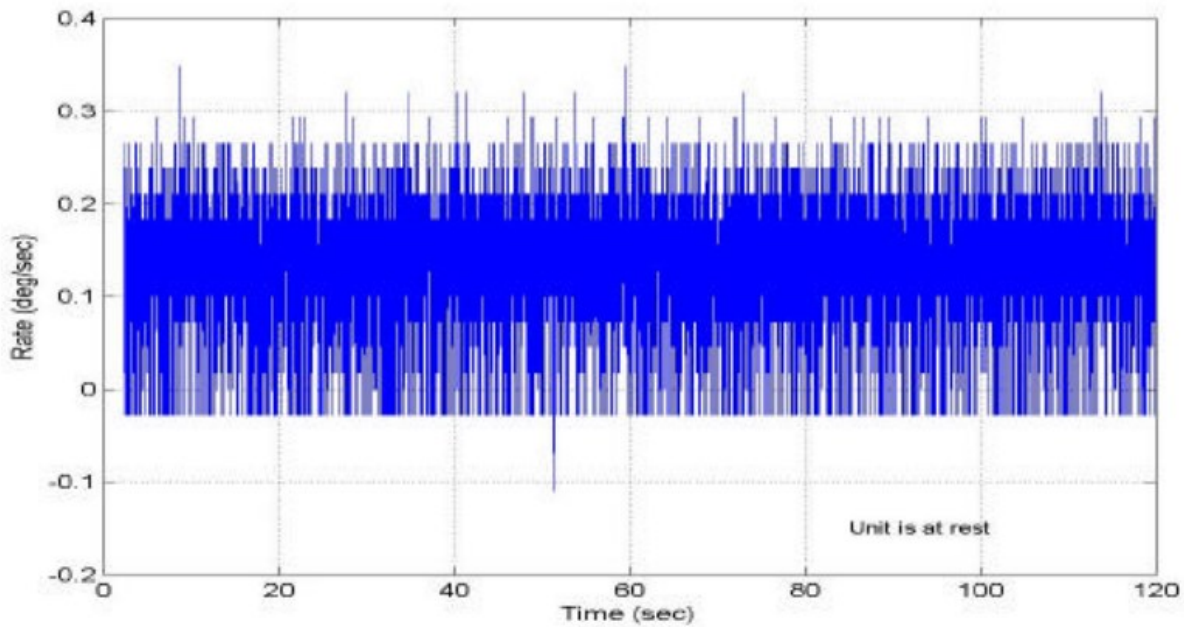
Temperature effects



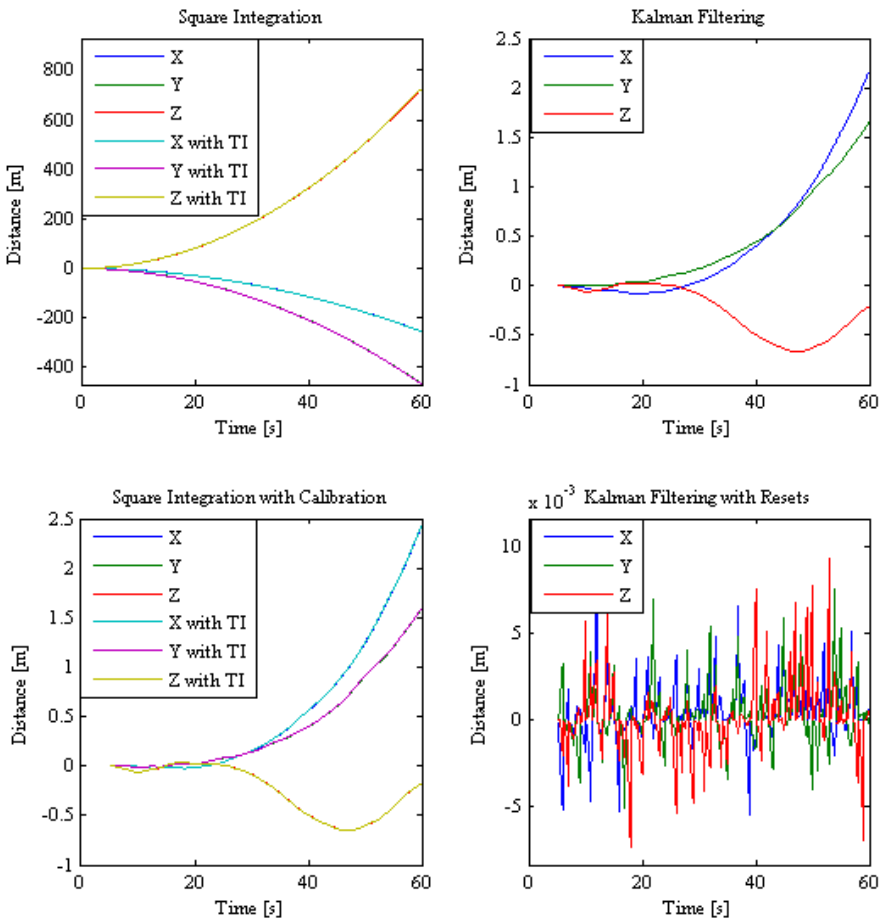


Output Signal Parameters

* What is a good sensor for INS?



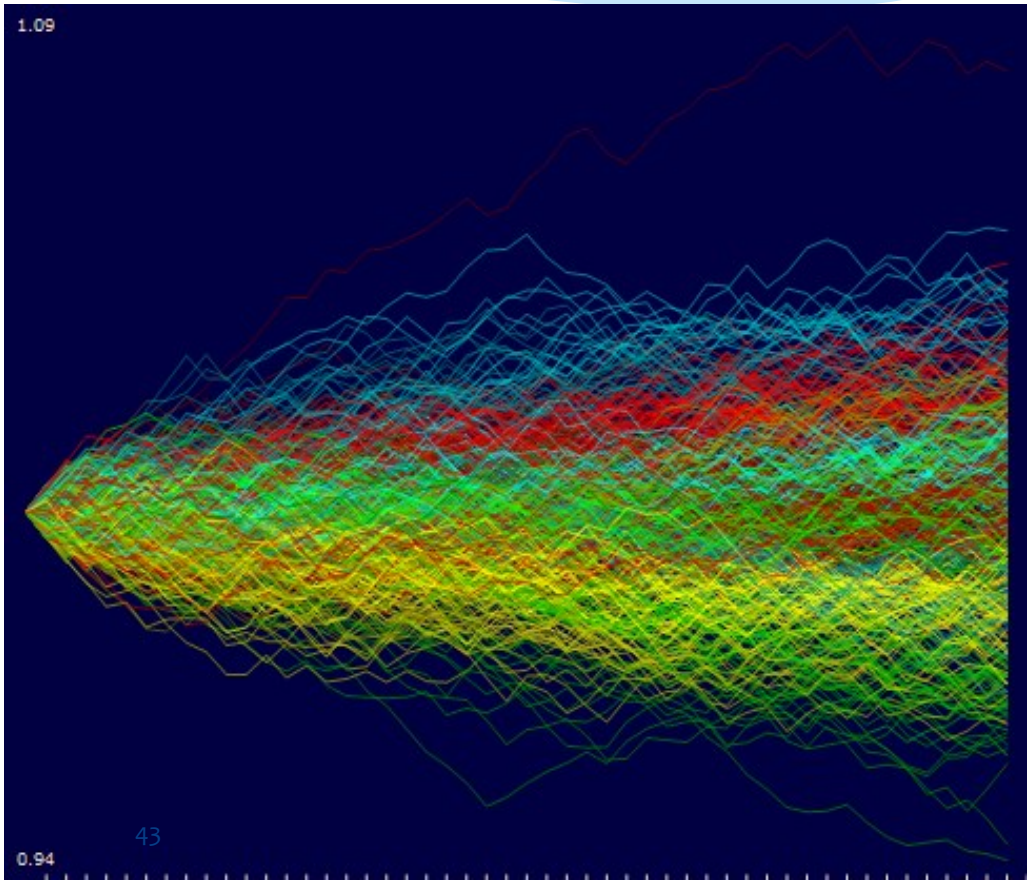
Testík



* cd d:\Projects\prj3D_MotionSensor\03_srcTest\
* [oData, iData, cData] = testINS(0,10,30,50,2)

Random Walk

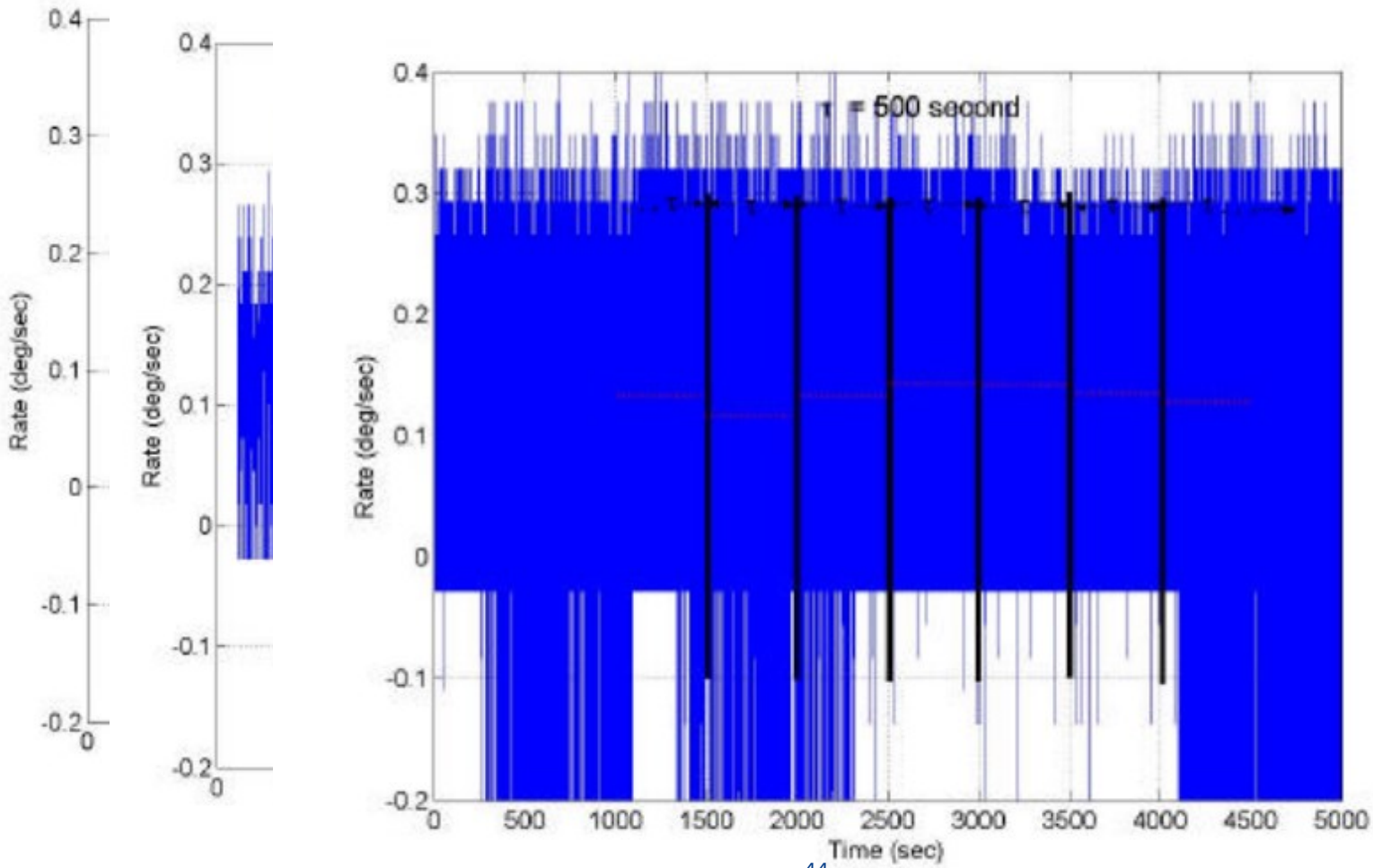
* Bias stability measurement
  * Output signal behavior

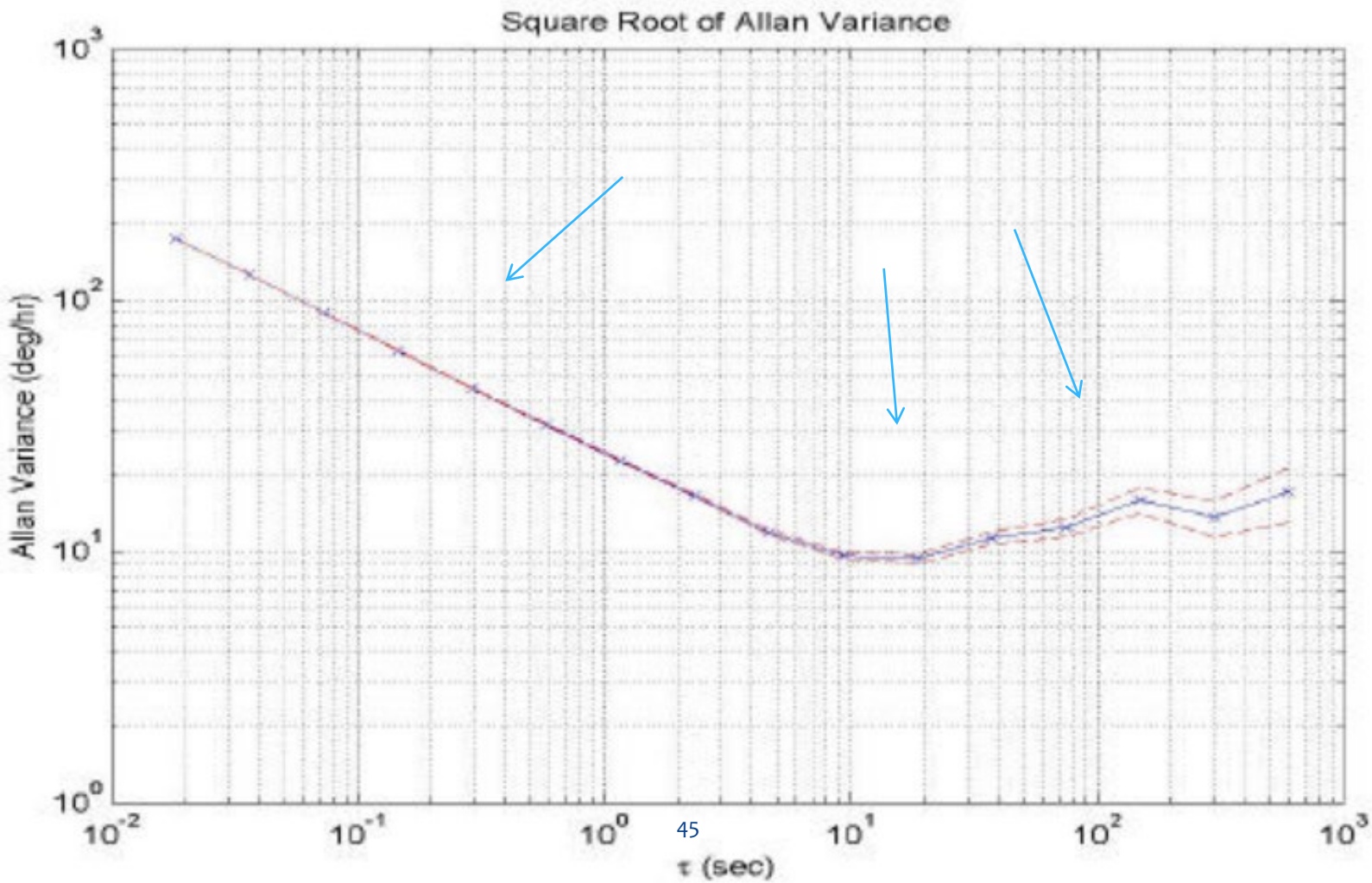


Output precision

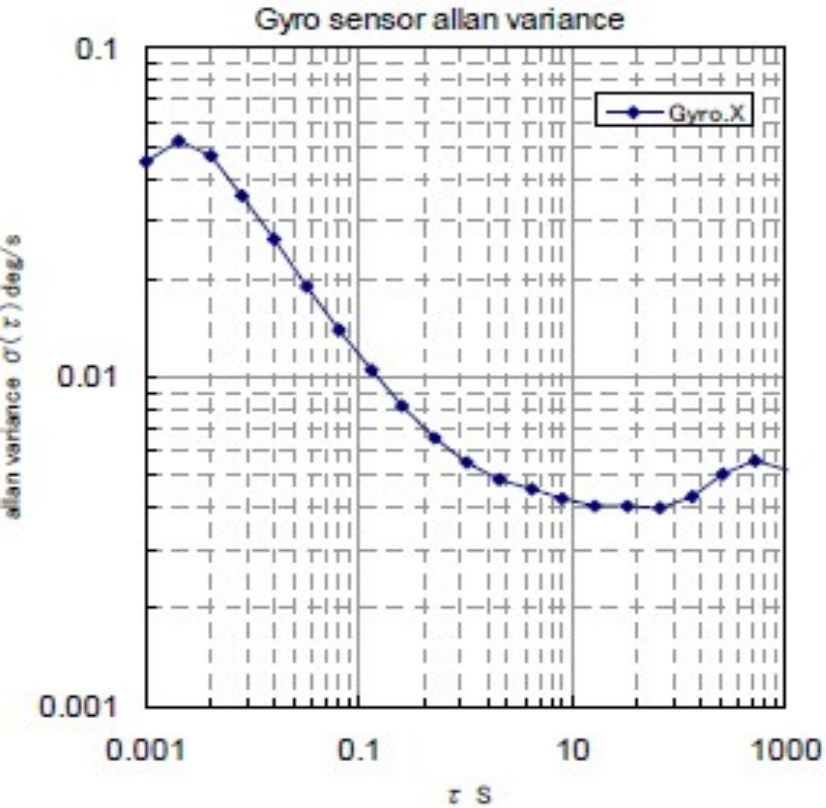
Allan Variance - movement of an average value in time

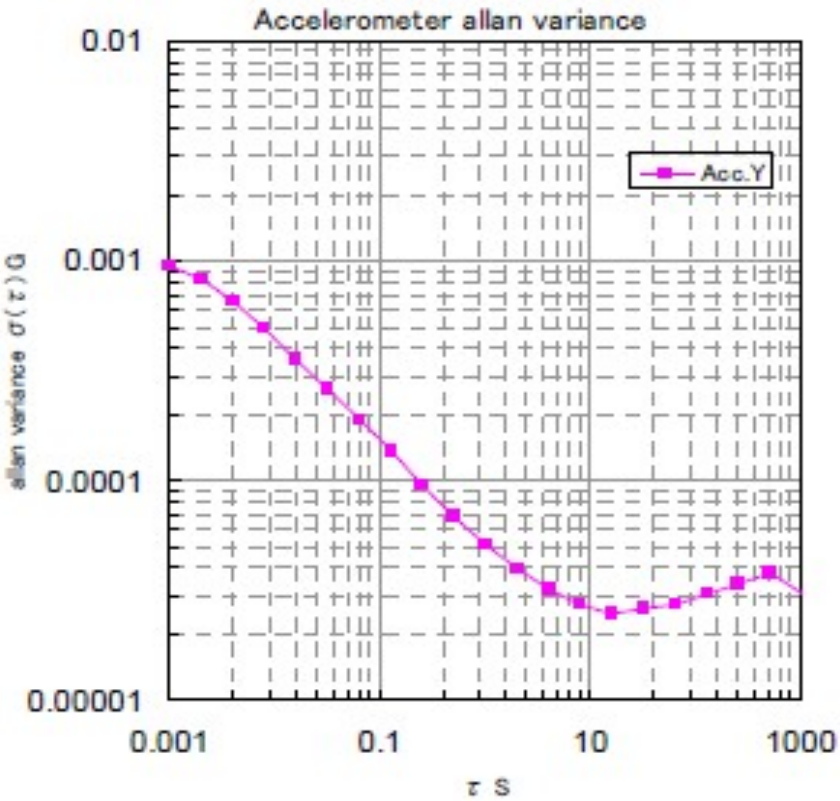
$$AVAR^2(\tau) = \frac{1}{2\cdot(n-1)}\sum_i \left(y(\tau)_{i+1} - y(\tau)_i\right)^2$$



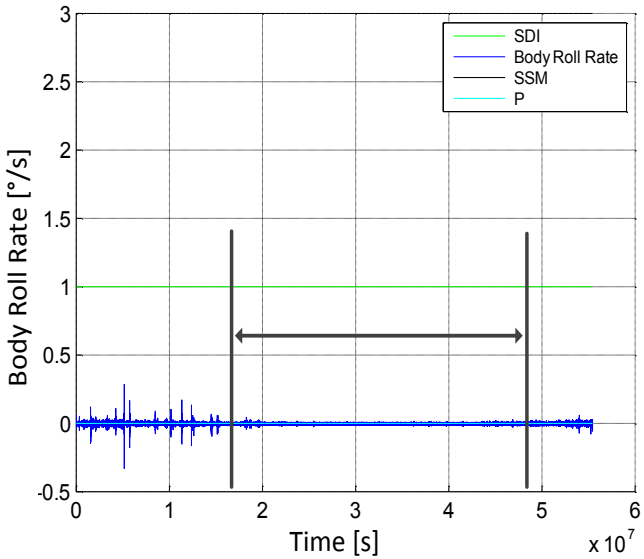

Square Root of Allan Variance
Allan Variance (deg/hr)
10^3
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
τ (sec)

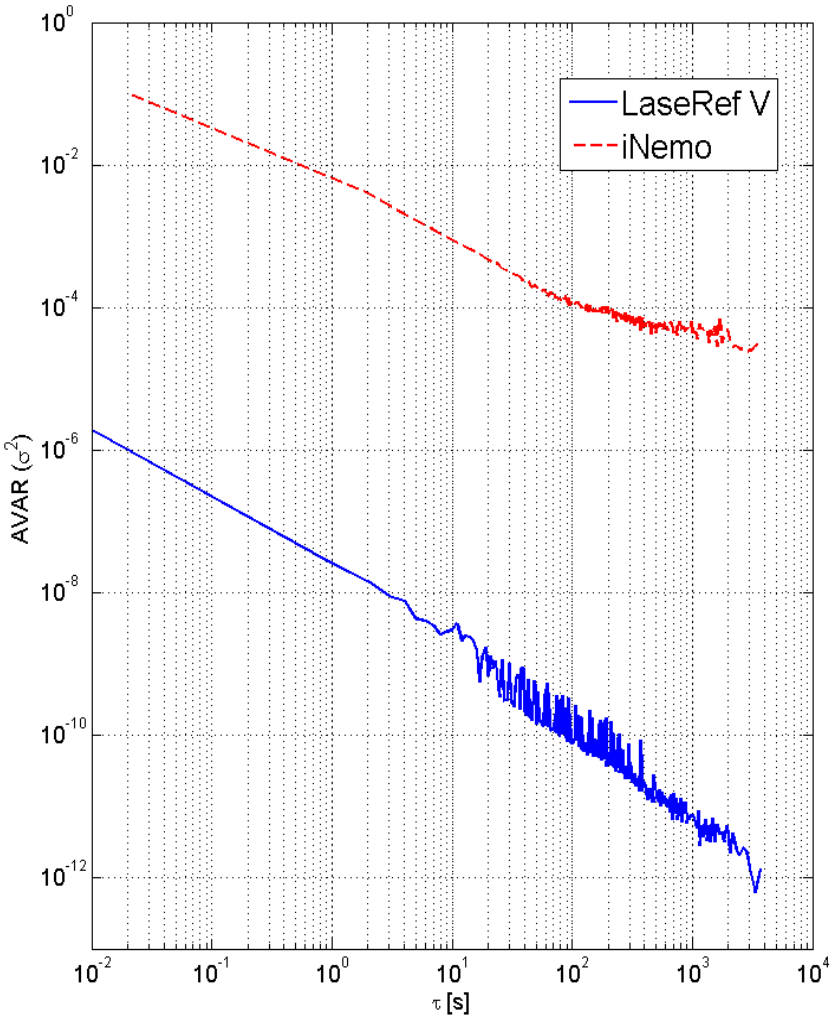
AVAR pro různé senzory





* RLG vs MEMS





Pačes, P. - Popelka, J. - Levora, T.: Advanced Display and Position Angles Measurement Systems *In: ICAS 2012 - 28th Congress of the International Council of the Aeronautical Sciences - Proceedings. Brisbane: ICAS - the International Council of the Aeronautical Science, 2012, p. P6.3.1-P6.3.14. ISBN 978-0-9565333-1-9.*

* **Zpátky na Zem**

Prague

* Latitude : 50, Longitude : 15, Height : 0
* ECEF from Latitude, Longitude, Height (**ellipsoidal**)
  * X : 3967.892 km
  * Y : 1063.193 km
  * Z : 4862.789 km
* Problem: Earth approximation (where is the center?)
  * Geiod
  * Ellipse
  * Real surface

http://www.oc.nps.edu/oc2902w/coord/llhxyz.htm

What happens if …

* … we set LLH = [0, 0, 0]?
* ECEF from Latitude, Longitude, Height (ellipsoidal)
  * X : 6378.137 km
  * Y : 0 km
  * Z : 0 km

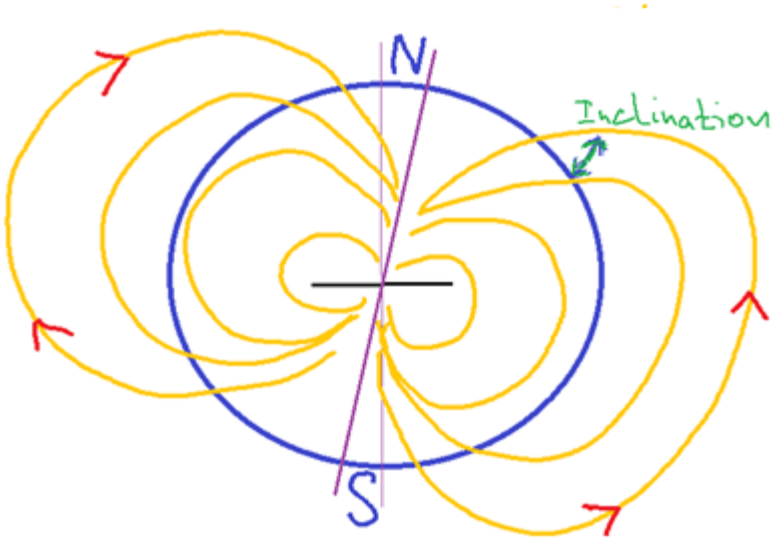
http://www.oc.nps.edu/oc2902w/coord/llhxyz.htm

Mag. Pole Země

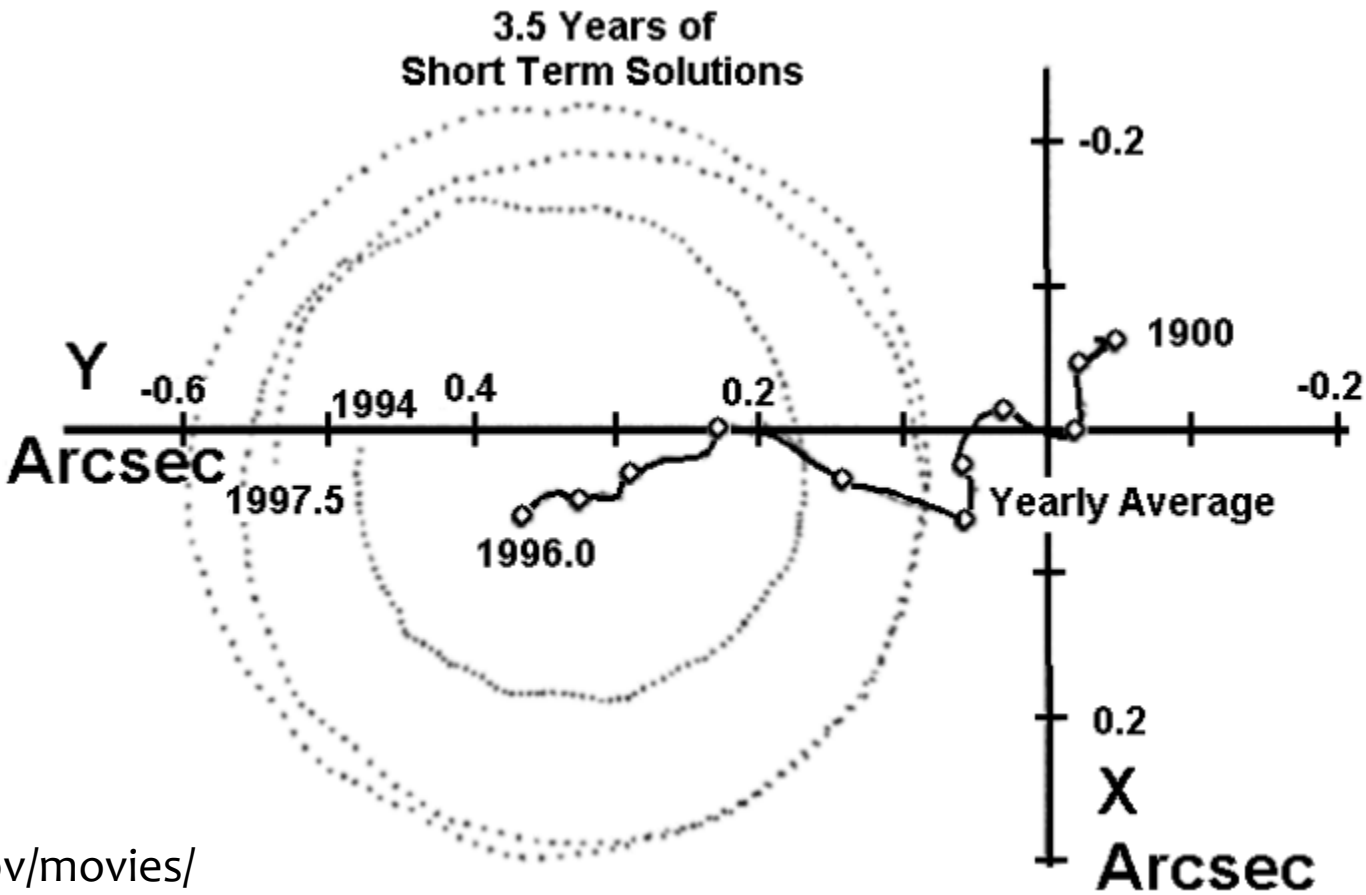
* Magnet – generates mag. field
  * Permanent Magnet
    – alignment of magnetic domains
  * Electro Magnet
    – current causing mag. field – depends on number of turns
* Permeability
  * $\mu = B/H$ > the higher value the more attraction
* Dipole
  * A magnet with two poles: North and South
* Does North pole of a magnet turns to the Earth's North Mag. Pole???

Earth's Magnetic Field

- **Almost** a dipole : plus and minus, North and South
- Confusion – double North
  - Geographic North Pole (True North)
  - Magnetic North Pole
    - Almost dipole
    - 11° from rotation axis
- Mag. Field
  - Horizontal at equator, vertical at poles
  - Used for navigation from 12 century
  - Compasses
    - N = North seeking
    - S = South seeking

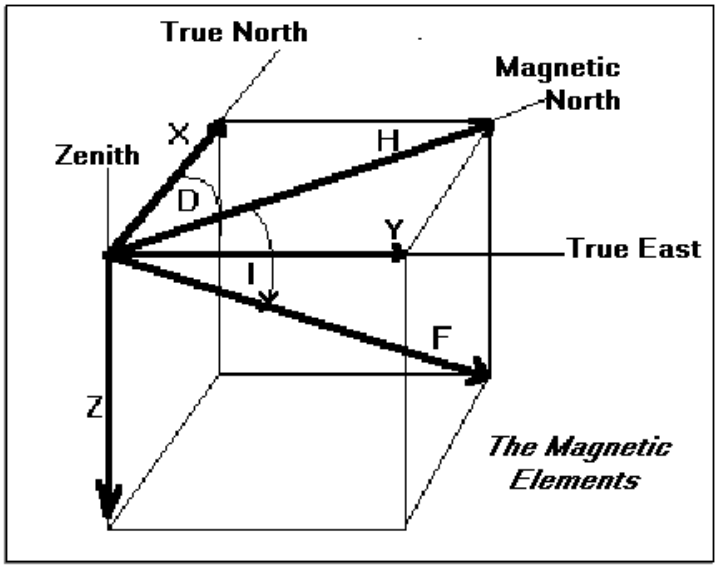


Travels of the Magnetic North



http://geomag.usgs.gov/movies/

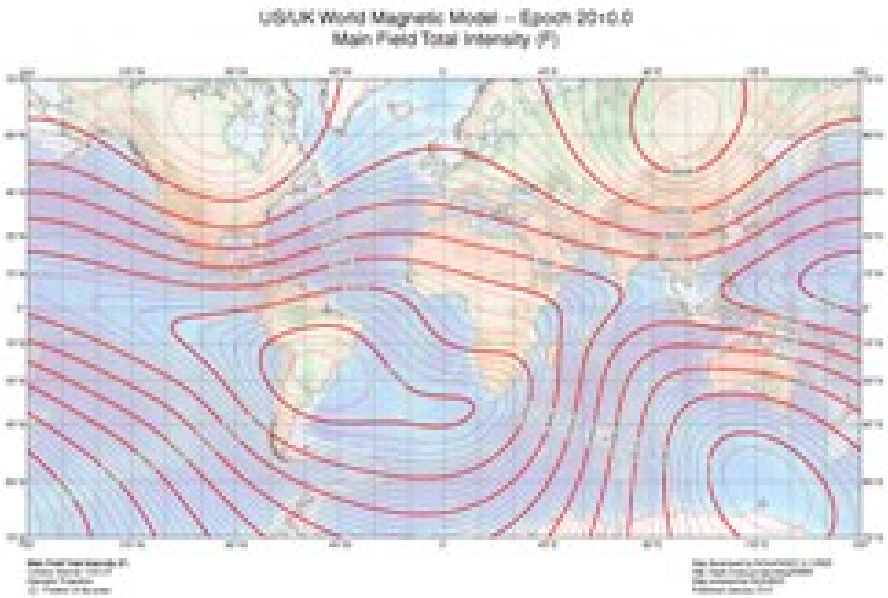
Description



* F - Total Intensity of the geomagnetic field
* H - Horizontal Intensity of the geomagnetic field
* X - North Component of the geomagnetic field
* Y - East Component of the geomagnetic field
* Z - Vertical Component of the geomagnetic field
* I (DIP) - Geomagnetic Inclination
* D (DEC) - Geomagnetic Declination (Magnetic Variation)

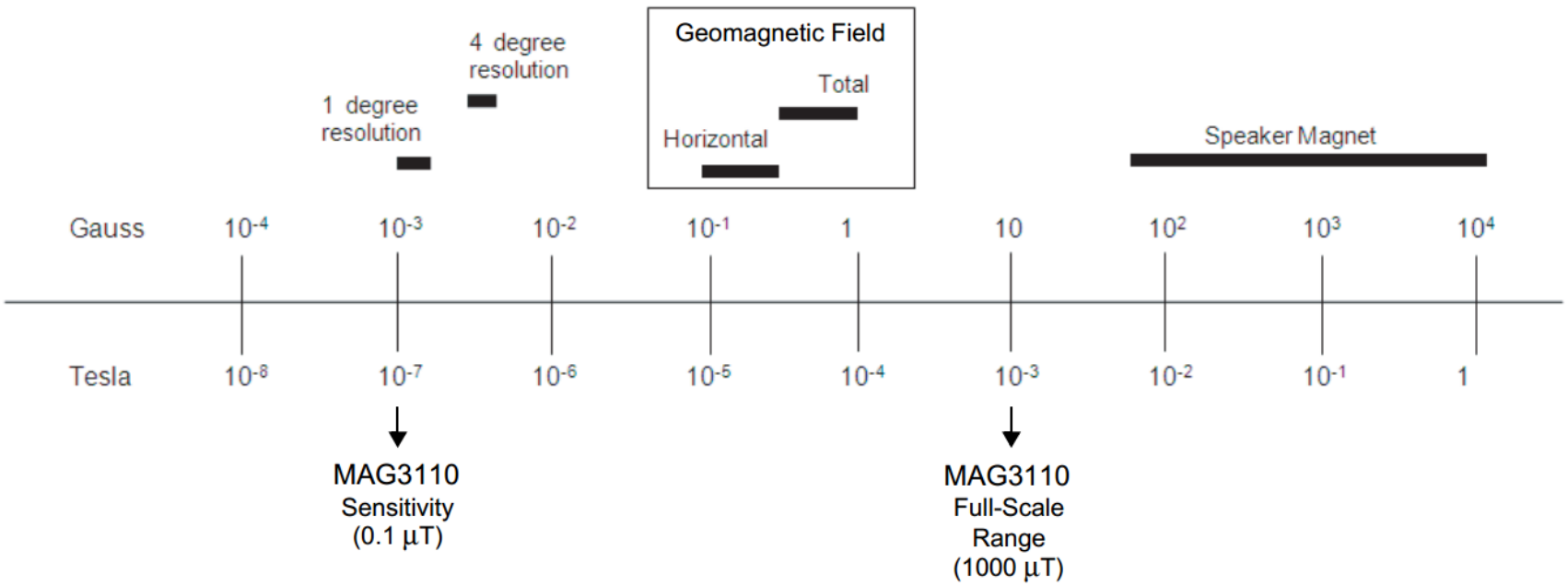
http://www.ngdc.noaa.gov/geomag/WMM/soft.shtml

Earth's Mag. Field Intensity



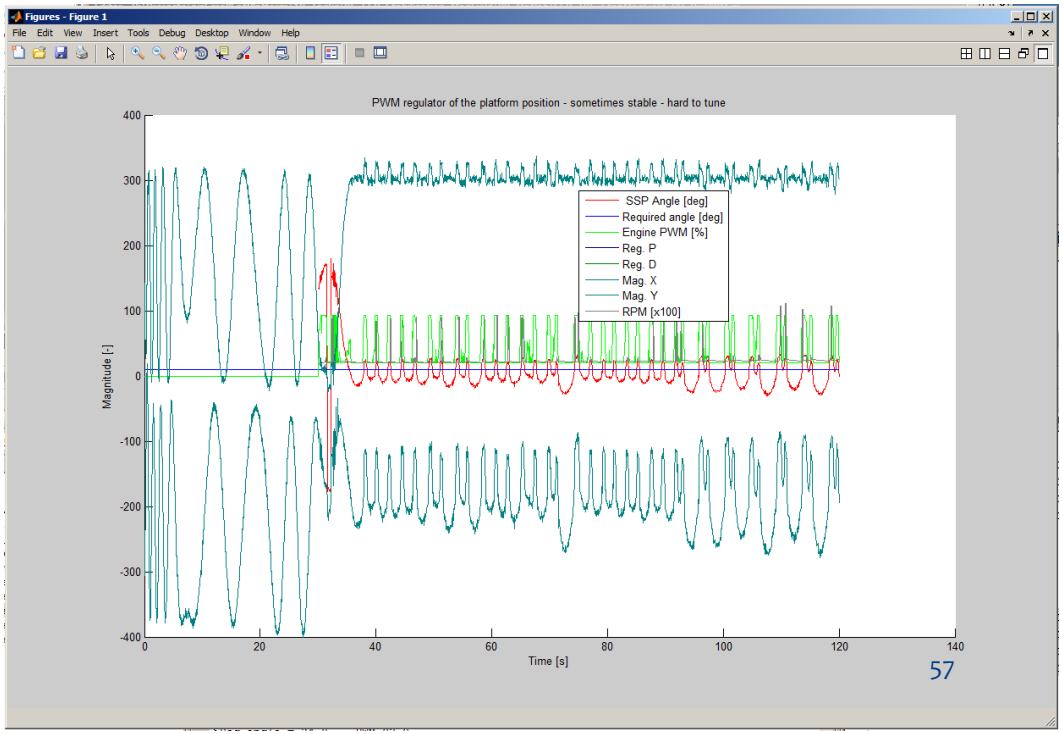
* Units: Gauss, or Tesla
  * 1 G = 100 uT, 1T = 10 kG
* Earth
  * 25 000 – 65 000 nT (easy conversion to G)
  * 0.3 – 0.6 G
* 25 000 nT on the equator, graph step 5 000 nT
* 65 000 nT on the pole
* Fridge magnet: 5 mT

http://www.ngdc.noaa.gov/geomag/WMM/DoDWMM.shtml


Geomagnetic Field
Total
Horizontal
4 degree resolution
1 degree resolution
Speaker Magnet
Gauss
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
Tesla
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
MAG3110
Sensitivity
(0.1 µT)
MAG3110
Full-Scale
Range
(1000 µT)

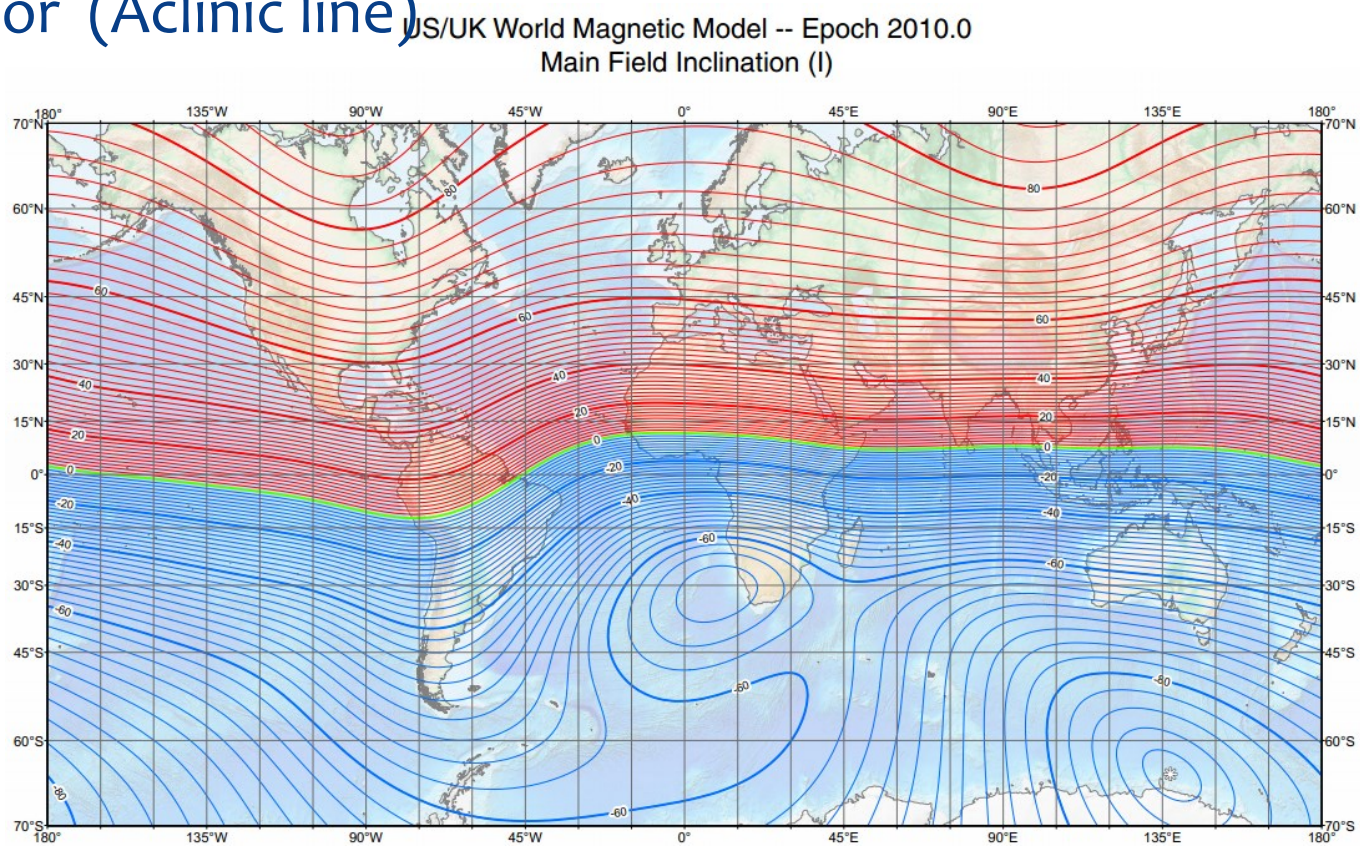
Magnetometr

* >> SSP_T06_StabMagField_PD_RwPWM



Inclination

* Angle of dip
* Straight equator and geomagnetic equator – varies in time
* Magnetic equator (Aclinic line)
* Step 20°



Sensors

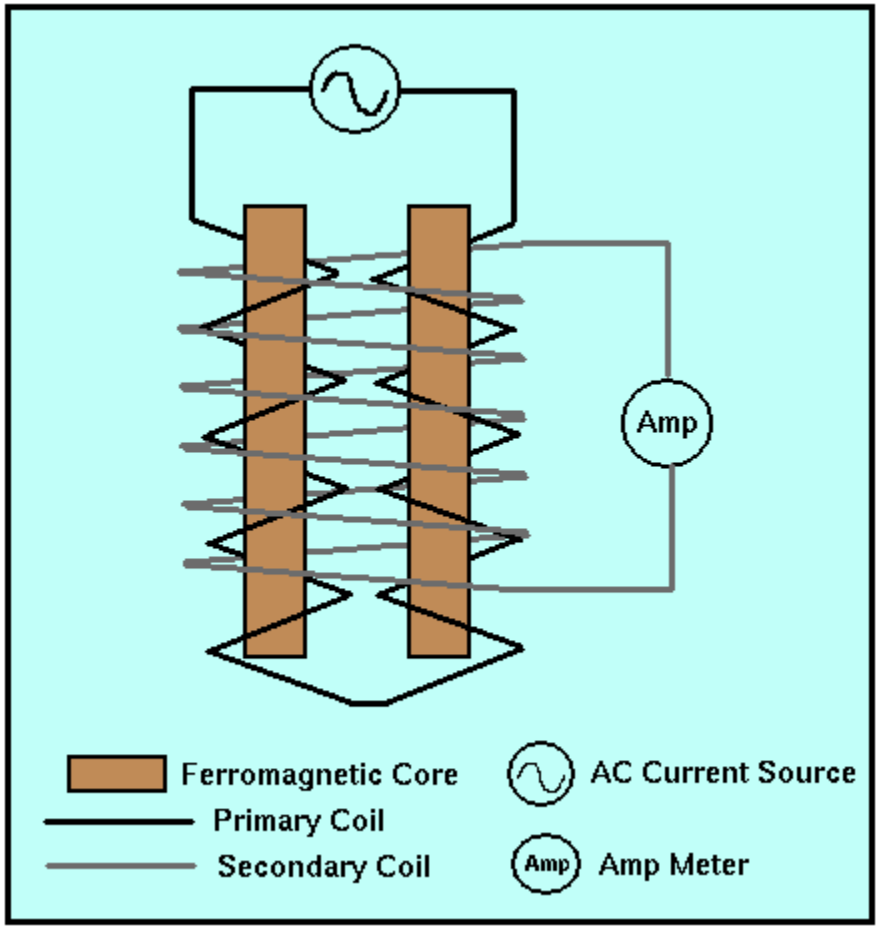
* Vector magnetometers
  * allows to determine direction of the field

* Fluxgate
  * Resolution: 6 nT (nano Tesla)
* Magneto-resistive – used for MEMS
  * anisotropic magnetoresistance (AMR)
  * Resolution: 1 uT (mikro Tesla)

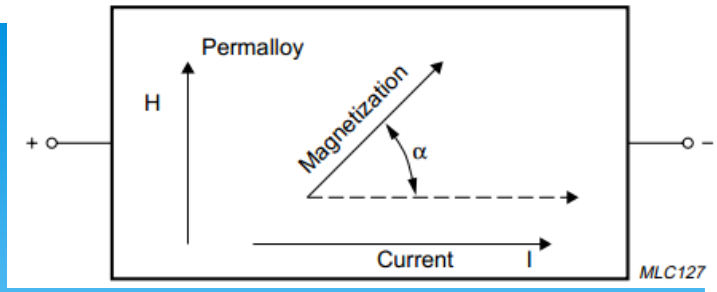
Fluxgate

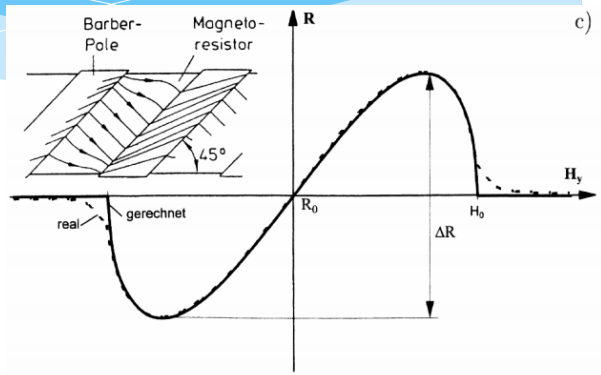
http://www.earthsci.unimelb.edu.au/ES304/MODULES/MAG/NOTES/fluxgate.html

* Excitation coil
  * Alternate current = mag. field
* Sensing coil
  * Mag. induction
  * With no ambient mag. Field => no output
* Closed magnetic loop improves linearity



Magnetoresistive Sensor

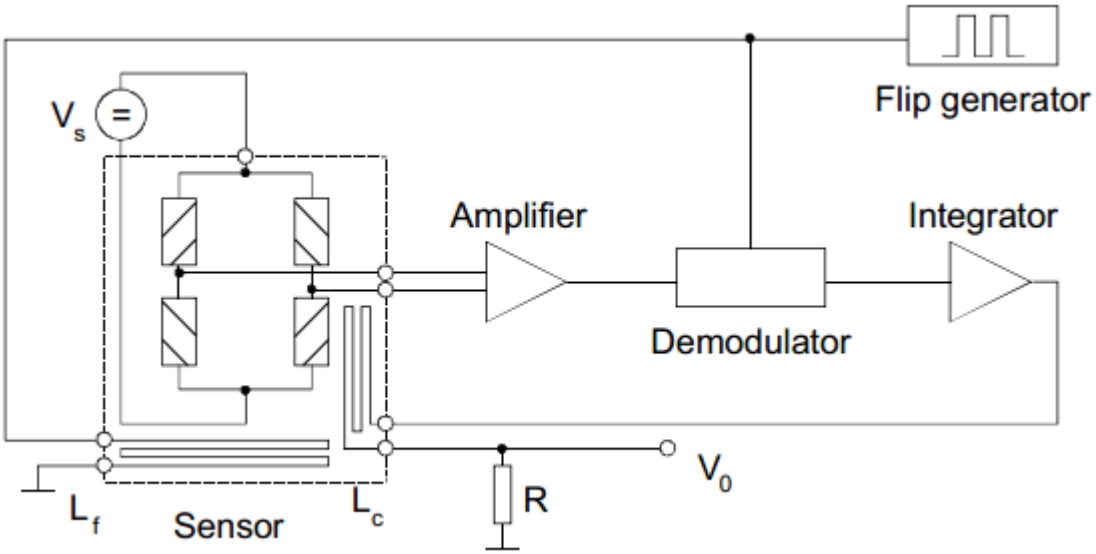




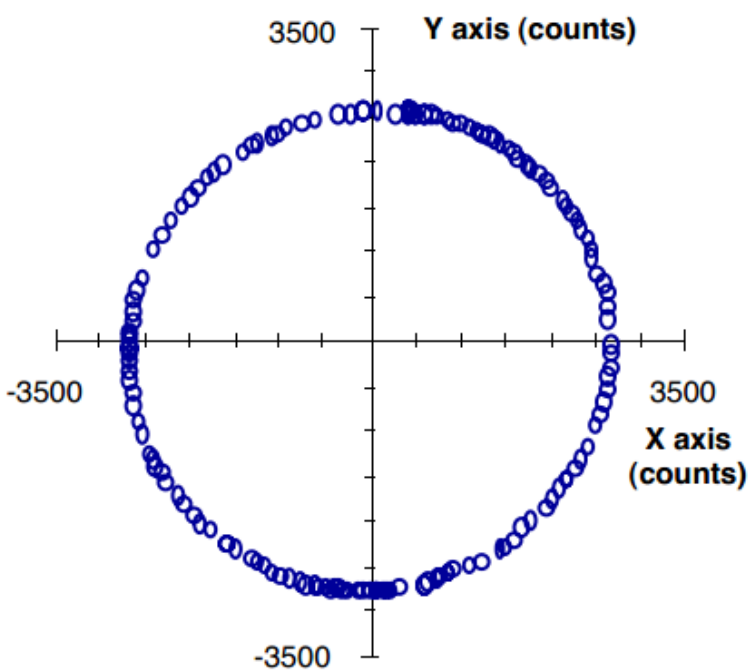
- Different shifts of energy levels of electrons under influence of mag. field
- Changes resistivity under mag. field

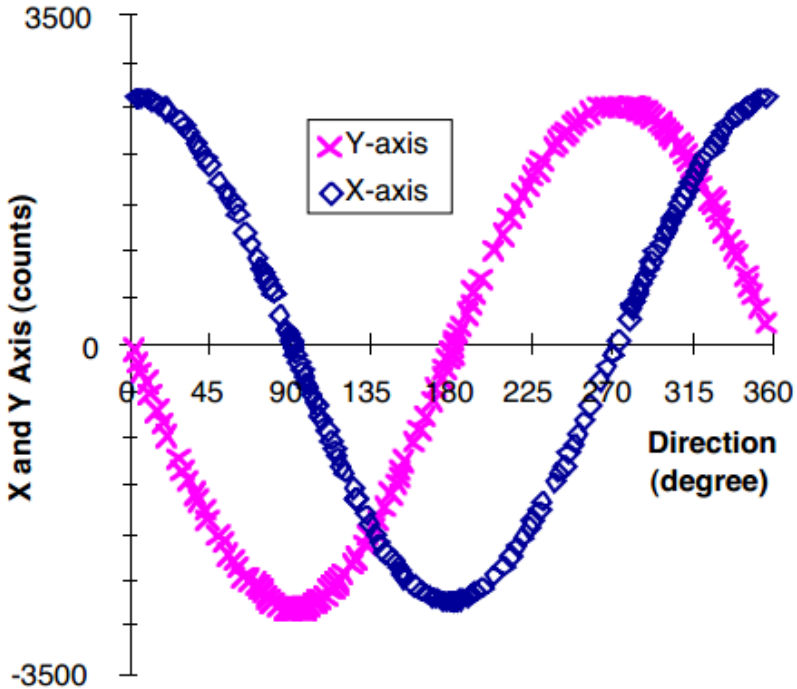
$$R = R_0 + \Delta R_0 cos^2 \alpha$$

- Barber pole
- Bridge with +/- compor
- Flipping coils
  - Remove offsets
- Compensation coils
  - Zero shift depends on R



Magnetometer readings





S/C Magnetometer

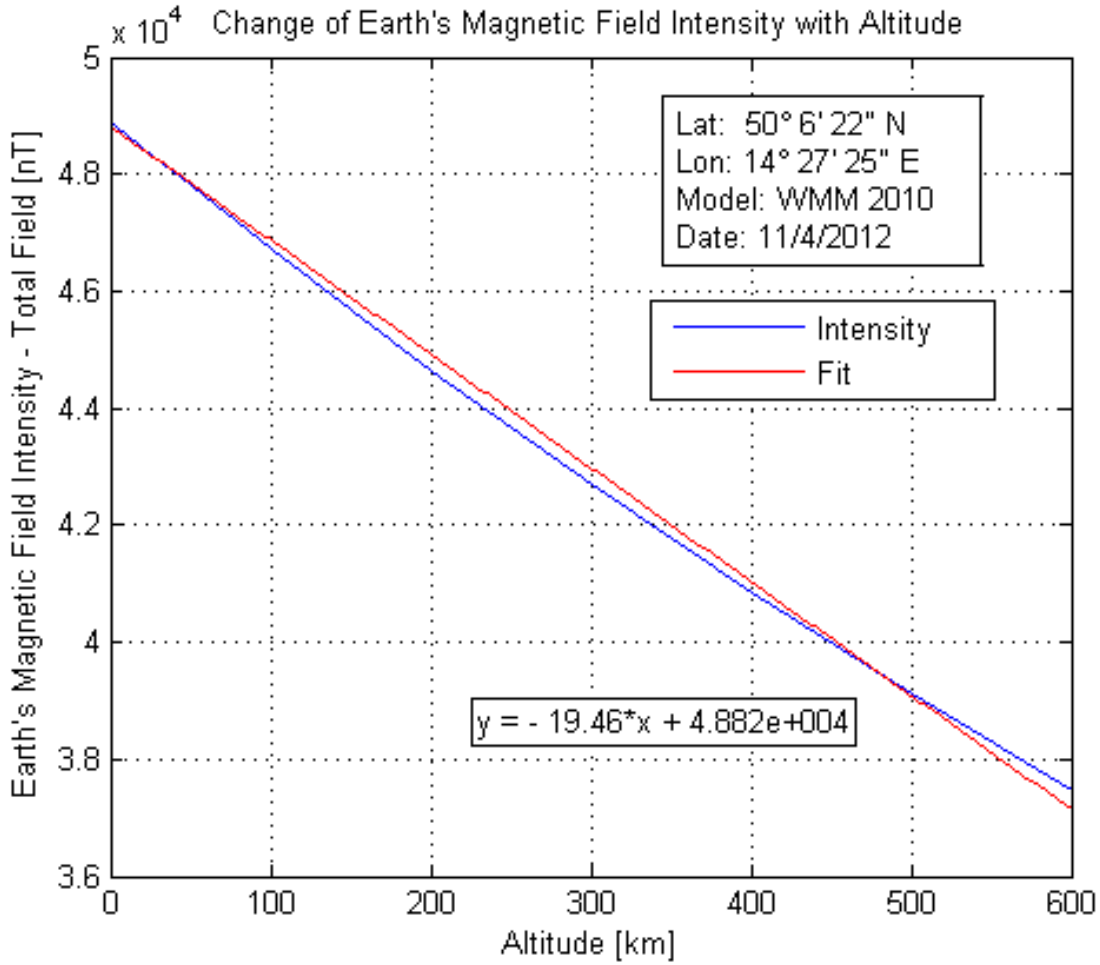
* Placed outside of the spacecraft on a boom
* In-flight calibration:
  * Spin stabilized S/C – allows to determine 8 of 12 calibration parameters
  * 3D stabilized S/C – problem,
    * we know the field magnitude from models

Spacecraft Stabilization

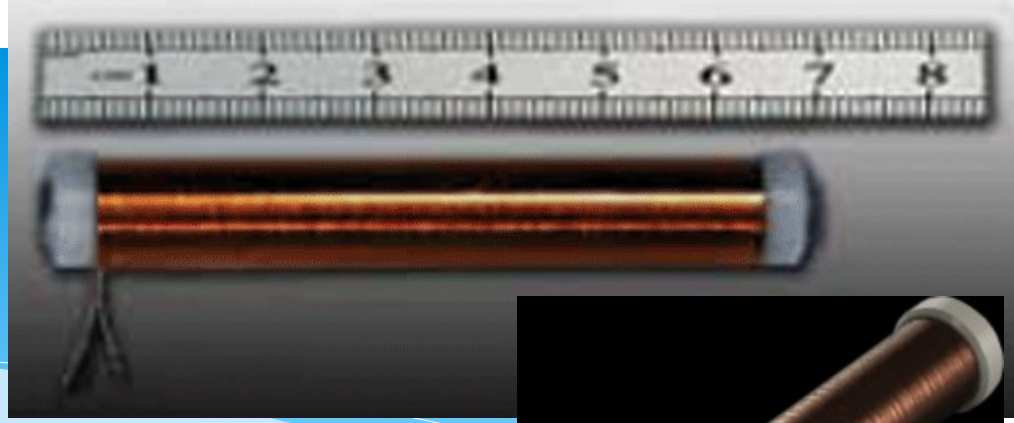
Magnetorquer (Rod)

* Interact with the Earth's mag. field
  * the higher the craft flies the weaker field (e.g. suitable for low Earth Orbits).
  * Lock problem (one axe aligned with the Earth's field)
* Switching current in a coil
* Three perpendicular coils - no moving parts
* Just electricity needed – no propellant required
* It influences the magnetometer
* The bigger craft the more current and intensity needed
* Slow changes – not suitable for precise attitude control – allows dumping of reaction wheels

Magnetic Field Intensity Change with altitude



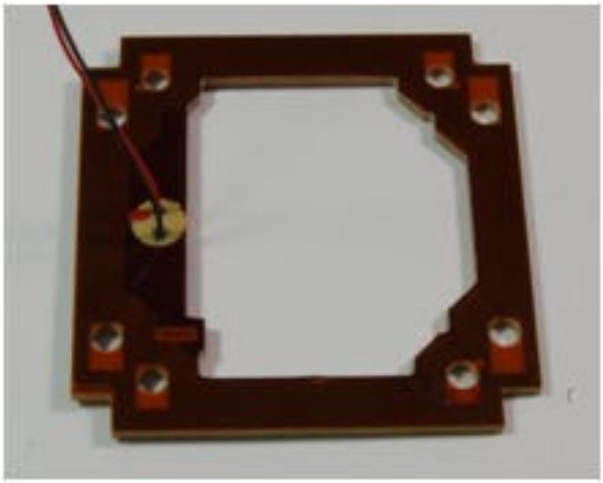
Magnetorquer



* Low-cost: **1000 Pounds**
* Mass: 50g
* Magnetic moment: 0.2Am^2 (Available systems up to 100 Am^2)
* The longer rod the higher momentum can be achieved (other method is wire in mag. field)
* They are useful only near perigee

Principle:

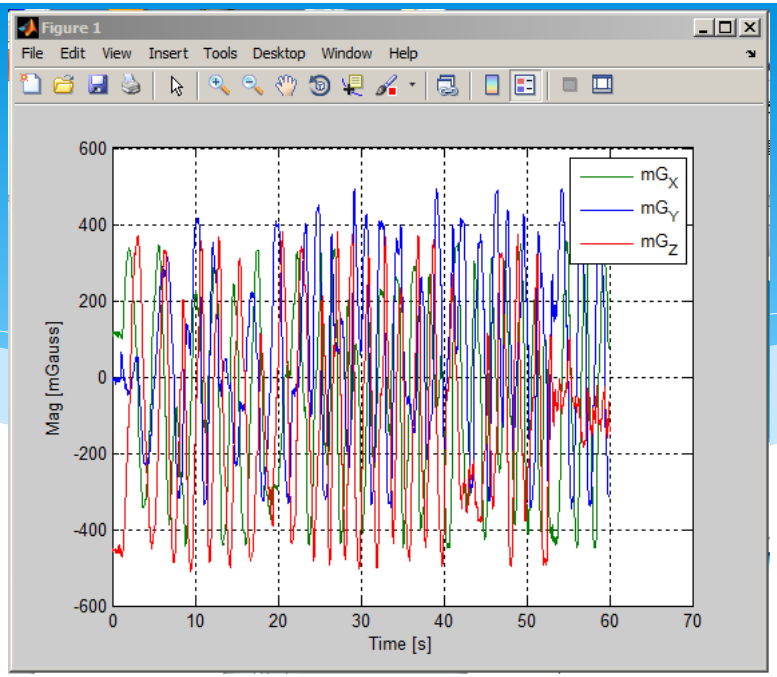
* Current (I) going through a wire (thumb in the direction of I)
* It generates mag. induction (B) (fingers shows direction of B)

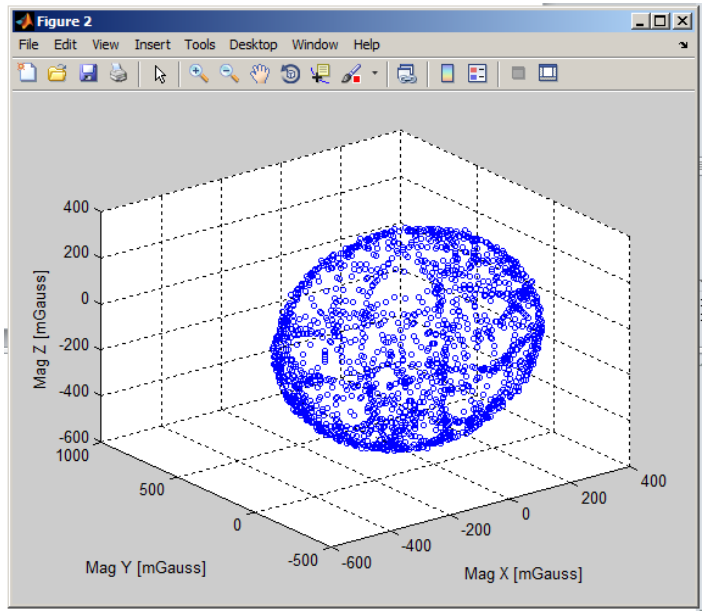


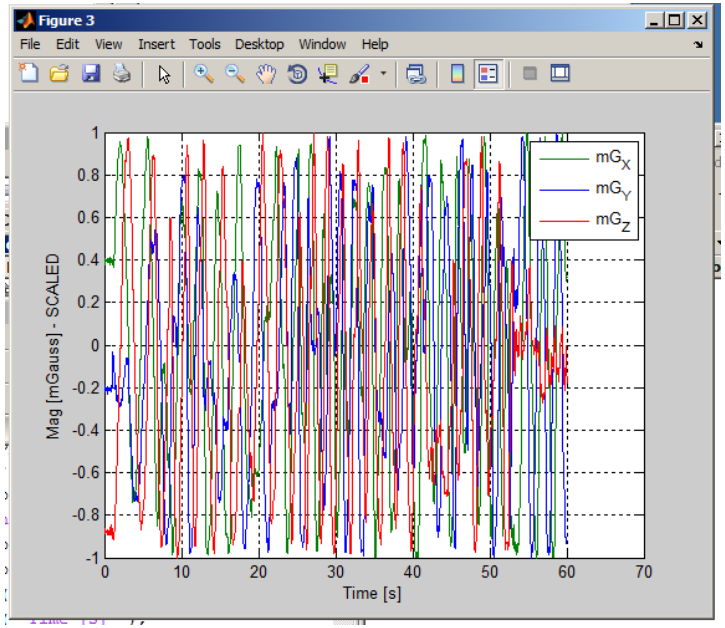
http://www.cubesatshop.com
http://www.clyde-space.com

Test

* SSP_T05_4_Mag_Calibration
* 3D magnetometer



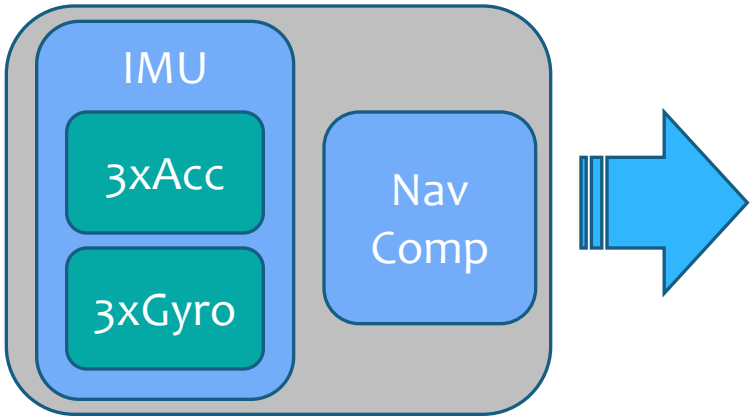




* **Navigační systémy**

Navigation Systems

* Inertial Navigation System drift 500 m/h



Data Source

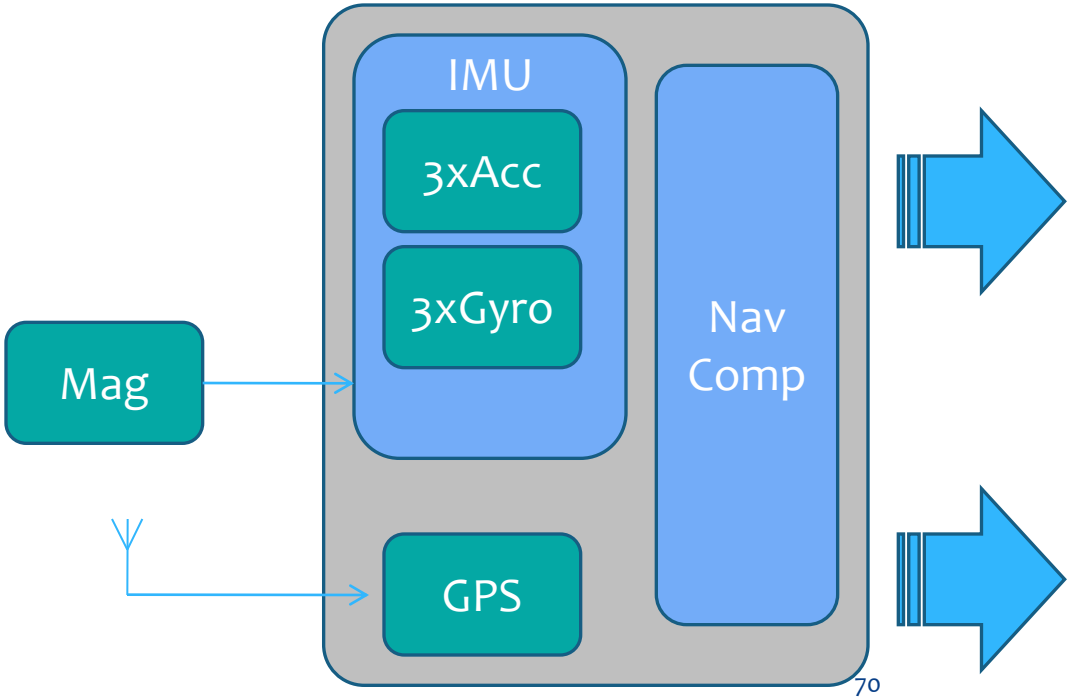
- Precise sensors

Outputs

- Yaw (Heading), Pitch, Roll
- Latitude and Longitude
- Velocity

Navigation Systems

* Attitude Heading and Reference System
* Drift +/- 1 m



Data Source

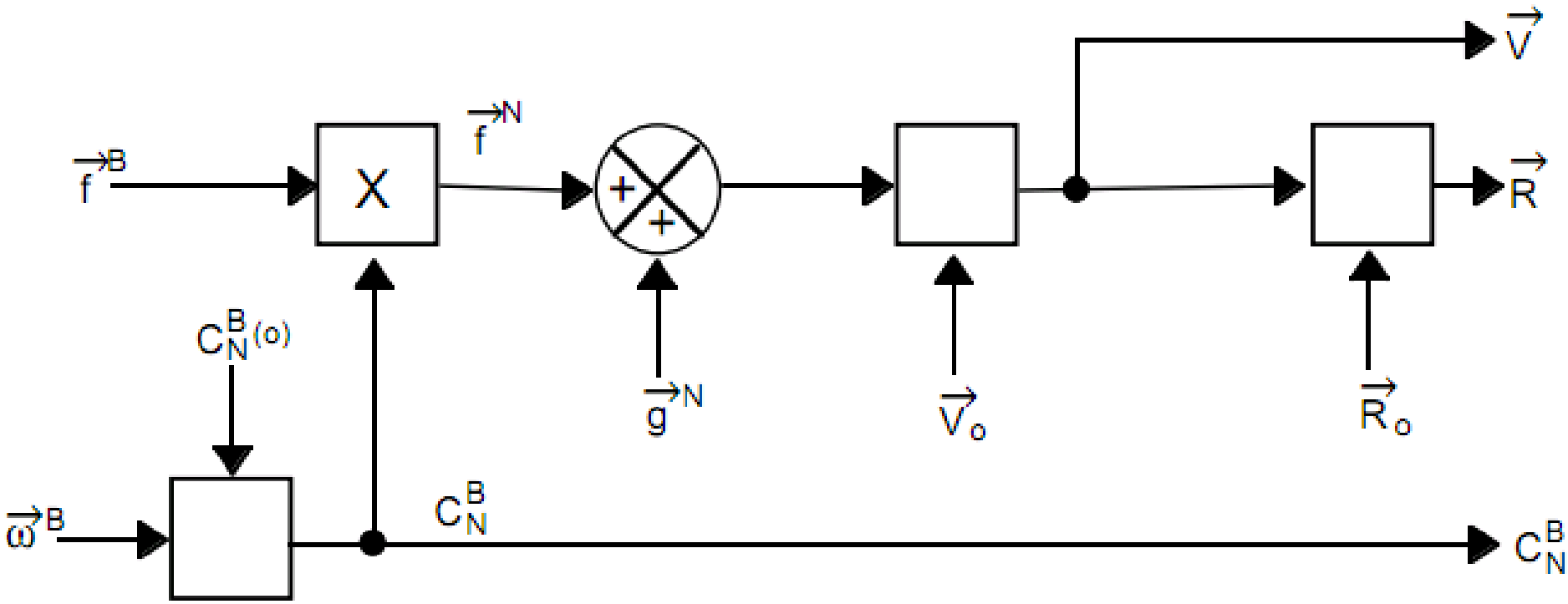
- Not so precise sensors, but with a GPS receiver and other data sources

Outputs

- Yaw (Heading), Pitch, Roll **estimations**

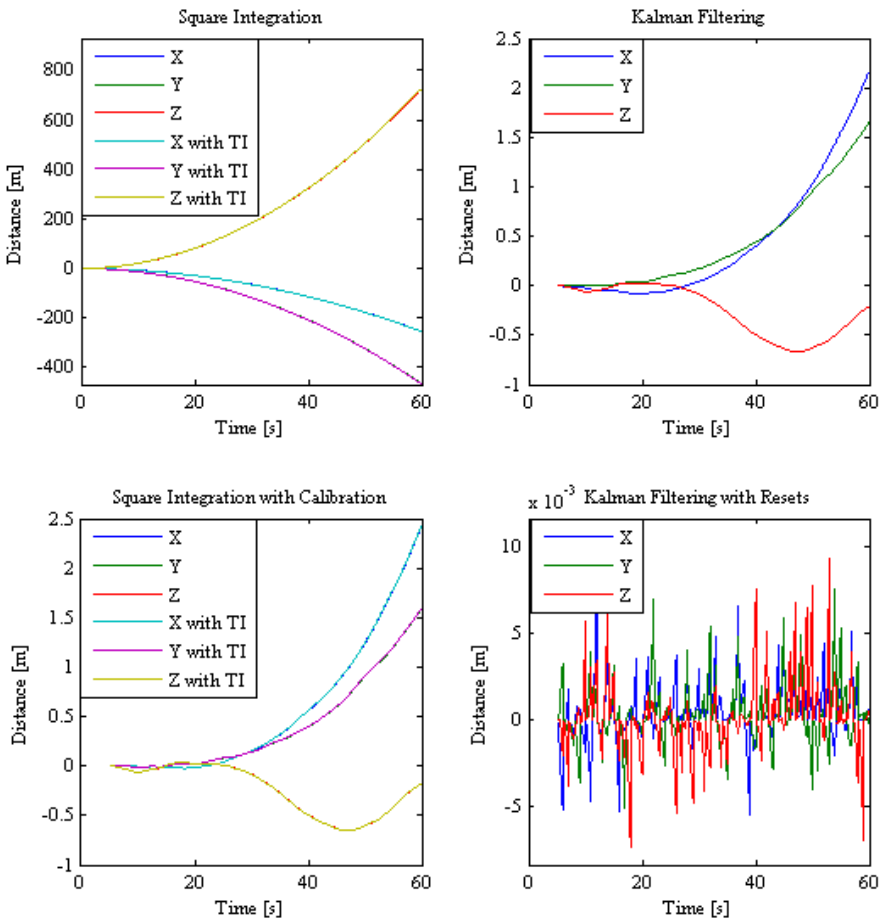
- Latitude and Longitude
- Velocity

Flat Earth Navigator



Testík

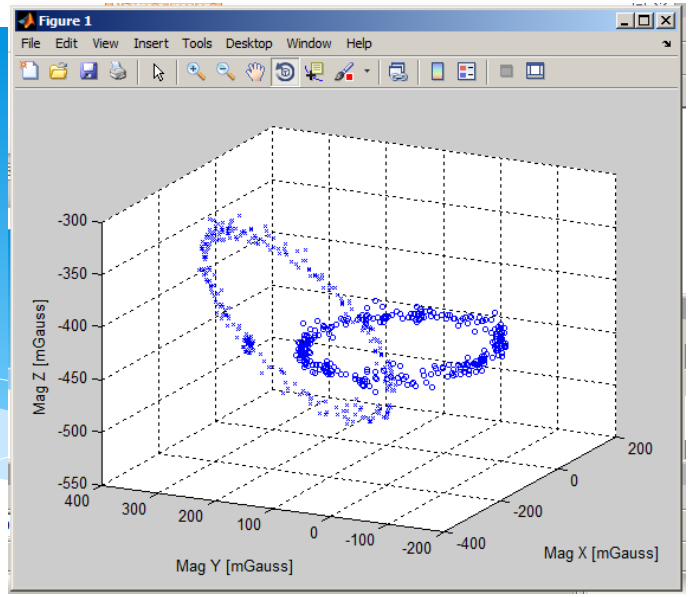
Jak se uplatňuje drift

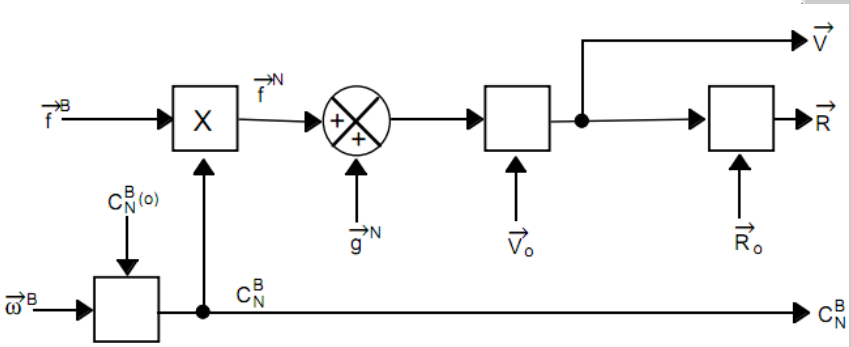


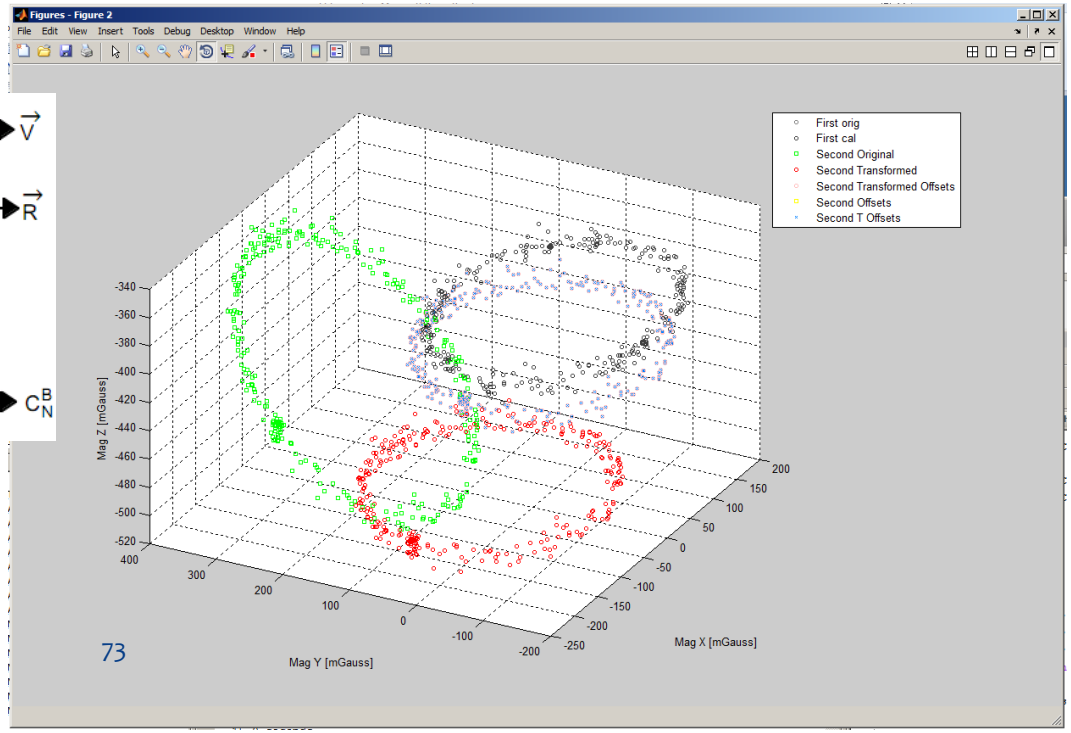
* cd d:\Projects\prj3D_MotionSensor\03_srcTest\
* [oData, iData, cData] = testINS(0,10,30,50,2)

Test

* Data rotation
  * Why are there ARS?
* SSP_T05_5_Mag_Independence.m

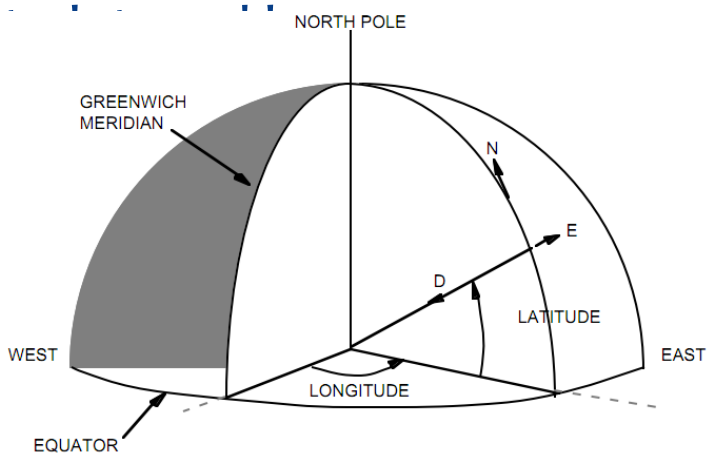






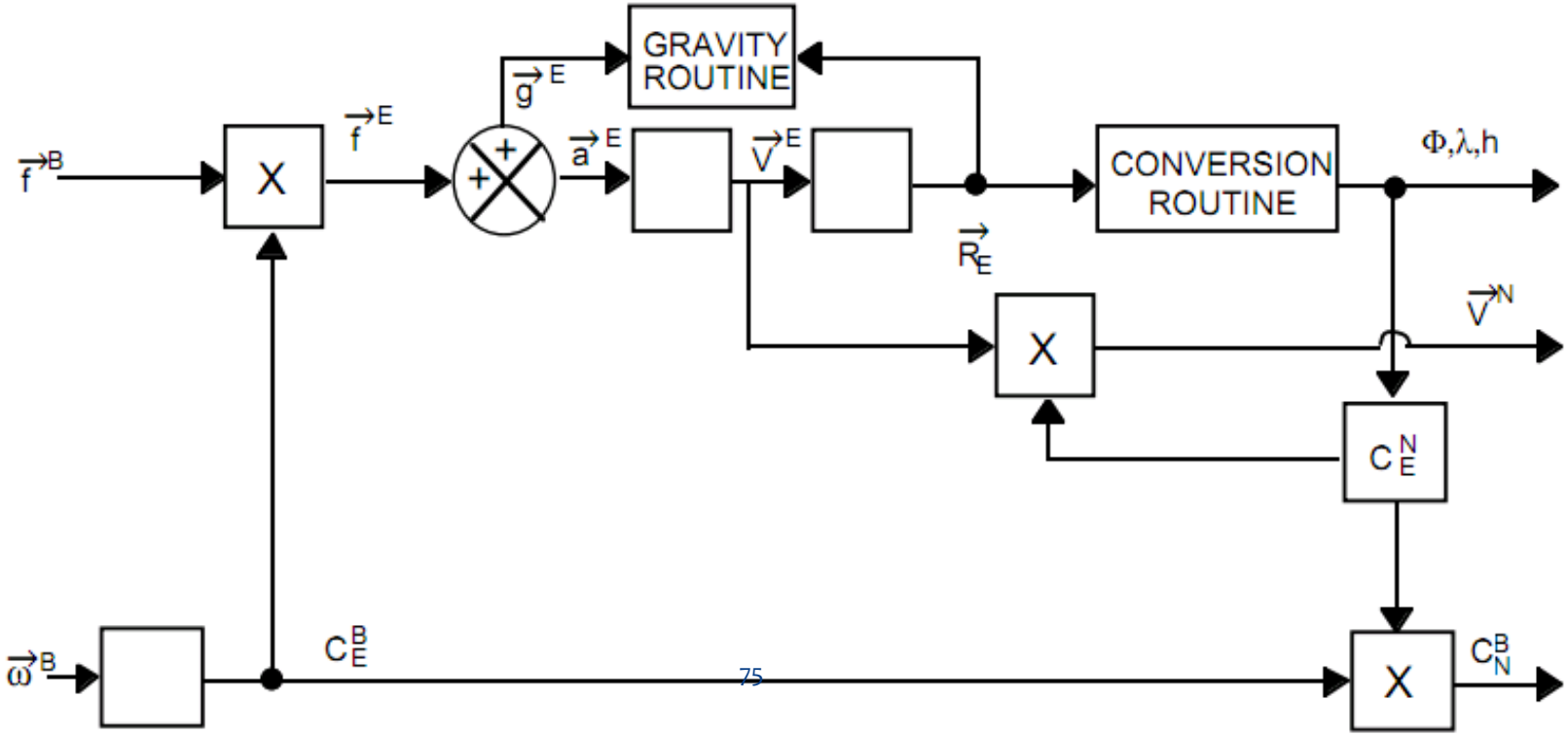
Non Rotating Spherical Earth

* NED coordinate system is not enough – but it is still used
* ECEF = latitude, longitude and altitude
  * => pitch and roll transformation
  * => alt. the same
  * Constant gravity => no more
    * The mathematical model is not precise as well (Earths density, etc.)
    * Causes altitude error



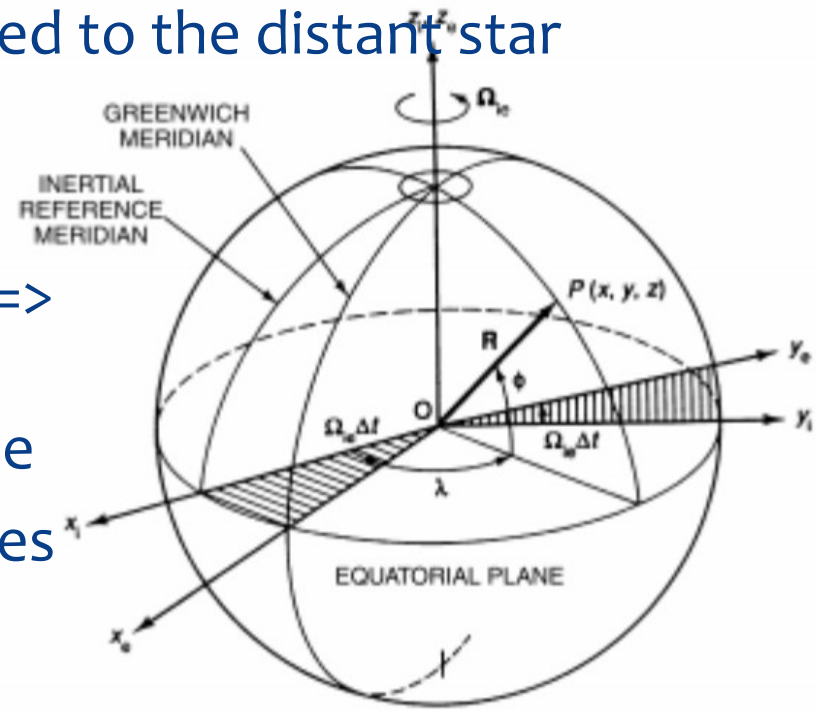
Non Rotating Spherical Earth

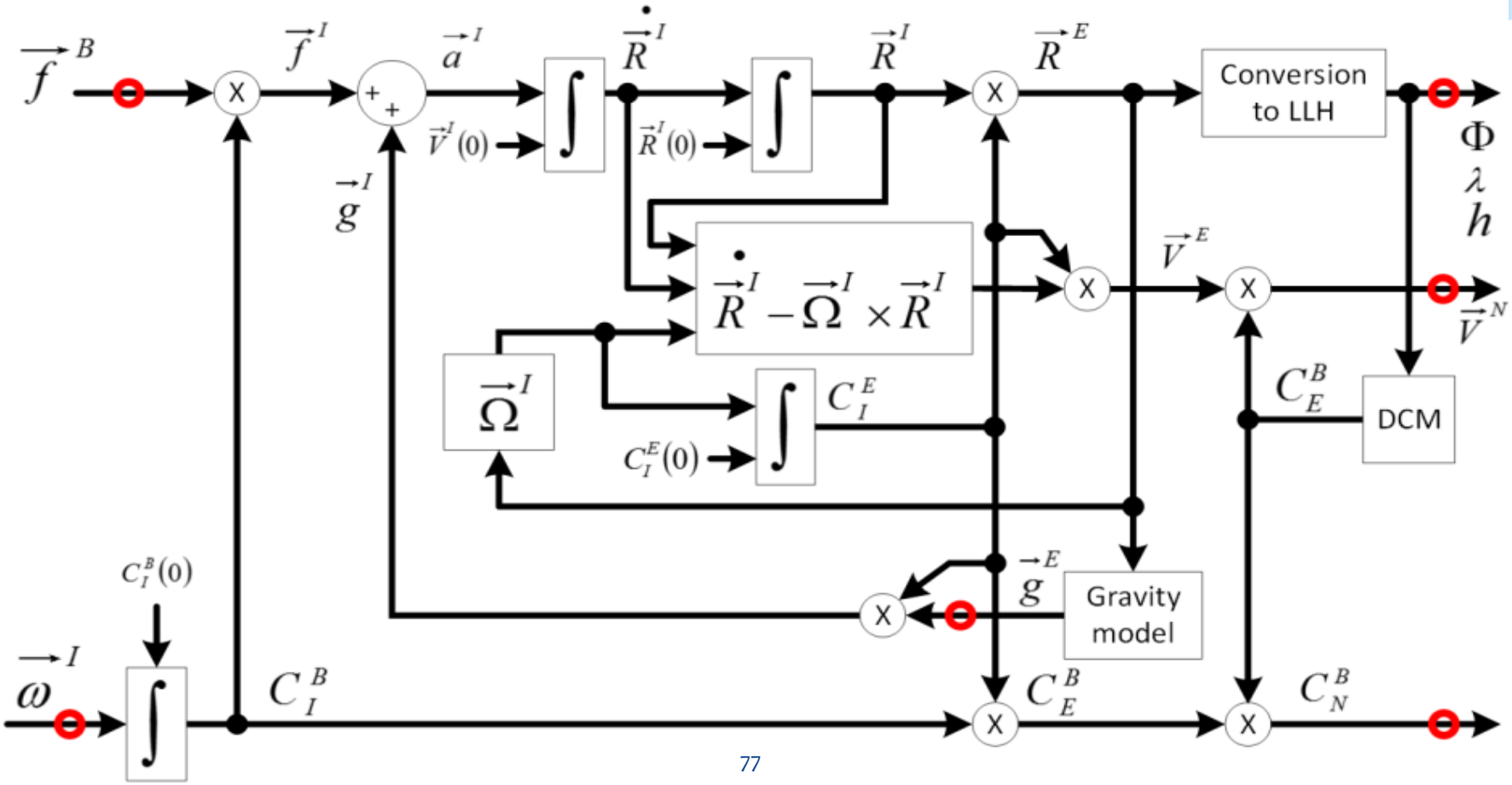
* The main difference is the gravity feedback and spherical coordinates, but the alignment is still in NED (it is not inertial frame) – Shuler oscillations apply
* Example: car traveling near poles



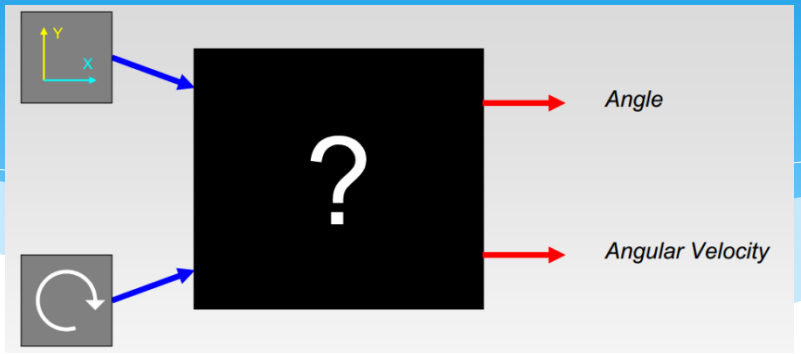
Rotating Spherical Earth

* Earth rotation is considered
  * We define inertial frame fixed to the distant star and center of the Earth
  * Same as ECEF in t=0
  * gyros and accelerometers => measurement with respect to the inertial frame
  * When we fly the Earth moves => example: balloon

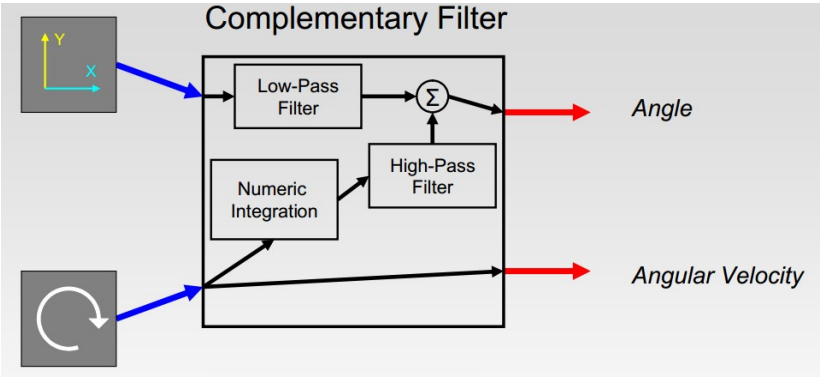


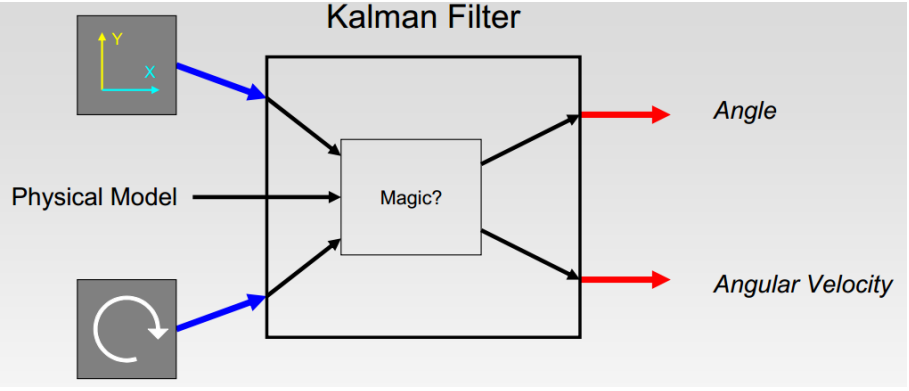

Conversion to LLH
DCM
Gravity model

Sensor Mapping

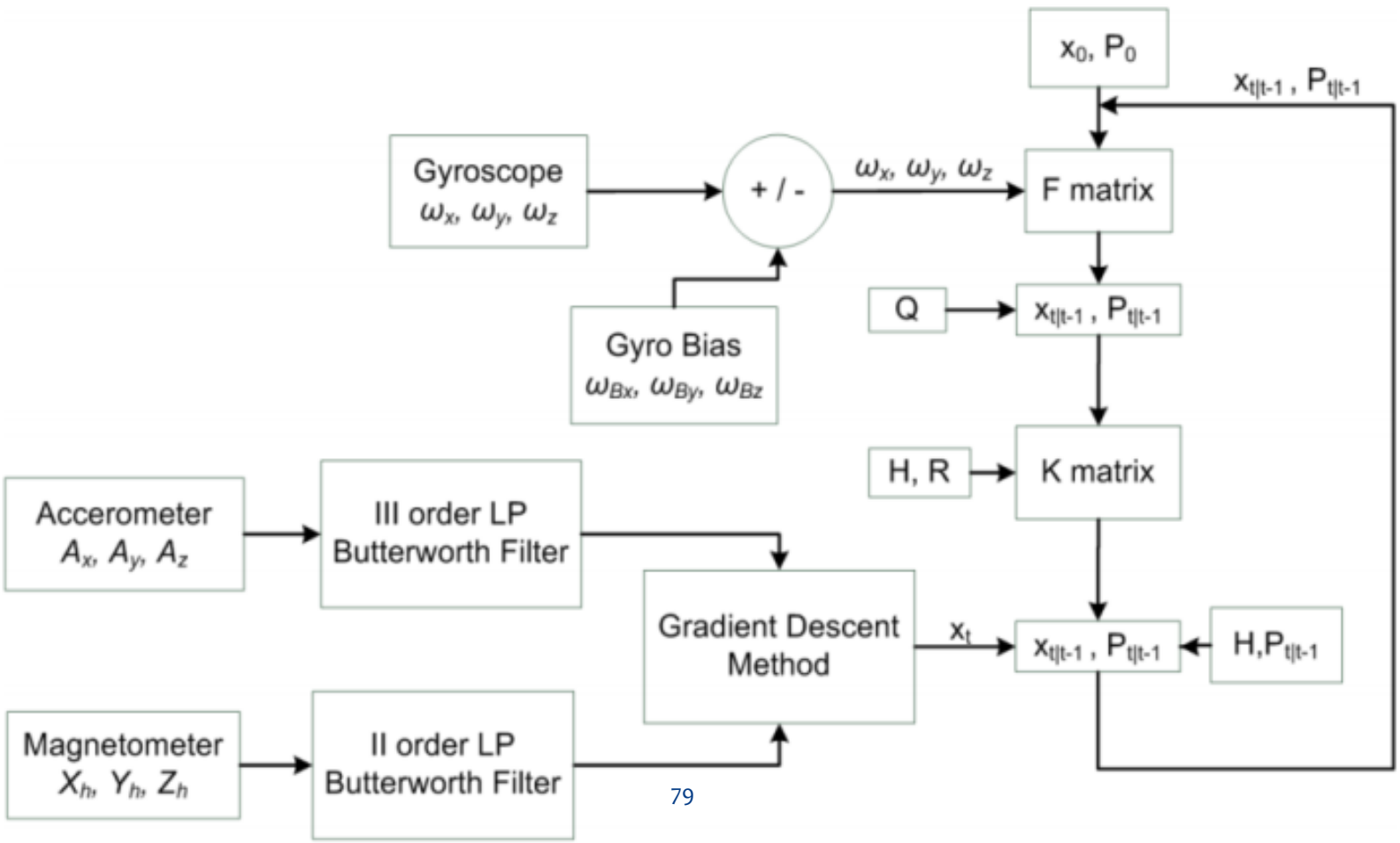


* Direct connection
* Single sensor method
* Complementary filter
* Other filters

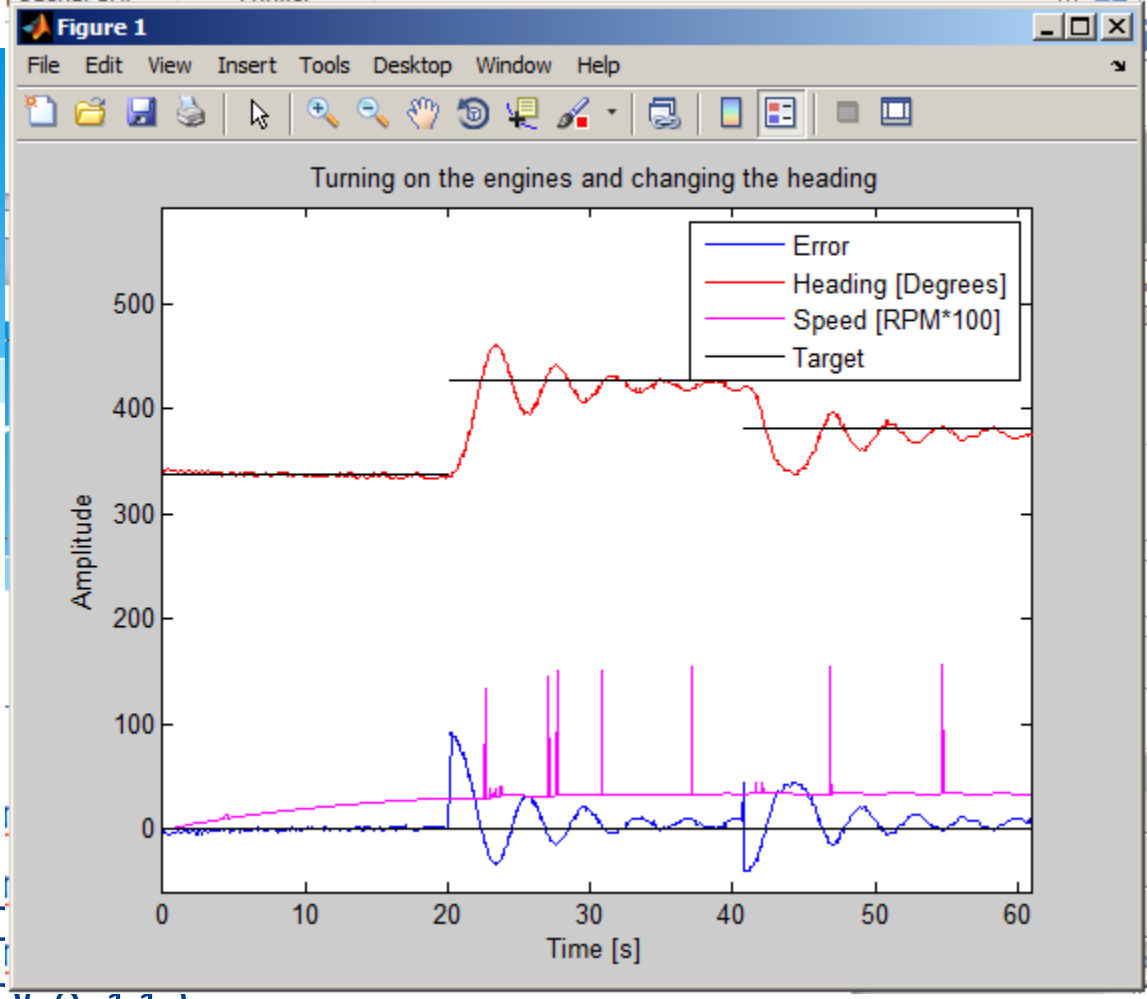




Other filters



* SSP stabilizace



* SSP_OpenTCP(0,3)
* iRetVal = SSP_StarTrackerLED
* iRetVal = SSP_StarTrackerLED(0, 1,1)
* iRetVal = SSP_StarTrackerLED(0, 2,1)
* iRetVal = SSP_StarTrackerLED(0, 3,0)
* preview(oCamera.vid)
* controledomodelo

Závěrem

* Senzory
* Akční členy
* Kalibrace výrazně zlepšuje užitné vlastnosti produktu
  * Mapy (SRTM)
  * Modely (GRACE)

Cestování s platformou SSP

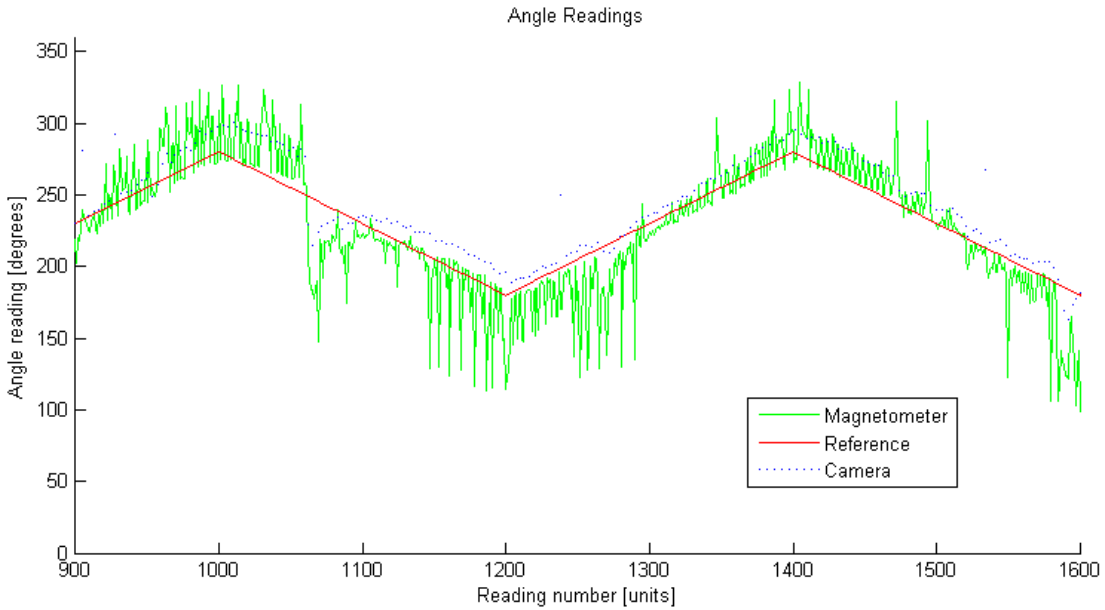
* Letiště a rentgeny (Istambul)

Prezentace

* Stánek Česká kosmická kancelář
  * IAC v Jižní Africe, Itálii, Číně

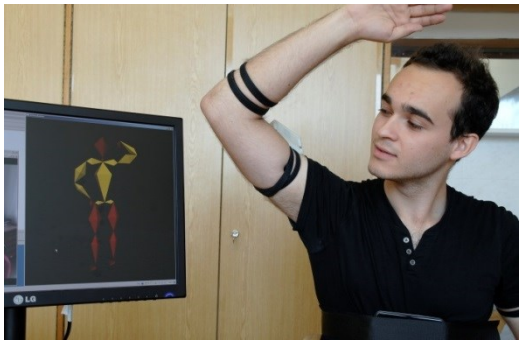
Kurzy

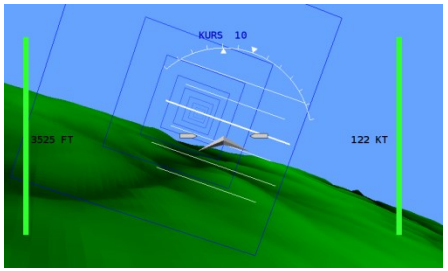
* ČR, Itálie, Pákistán

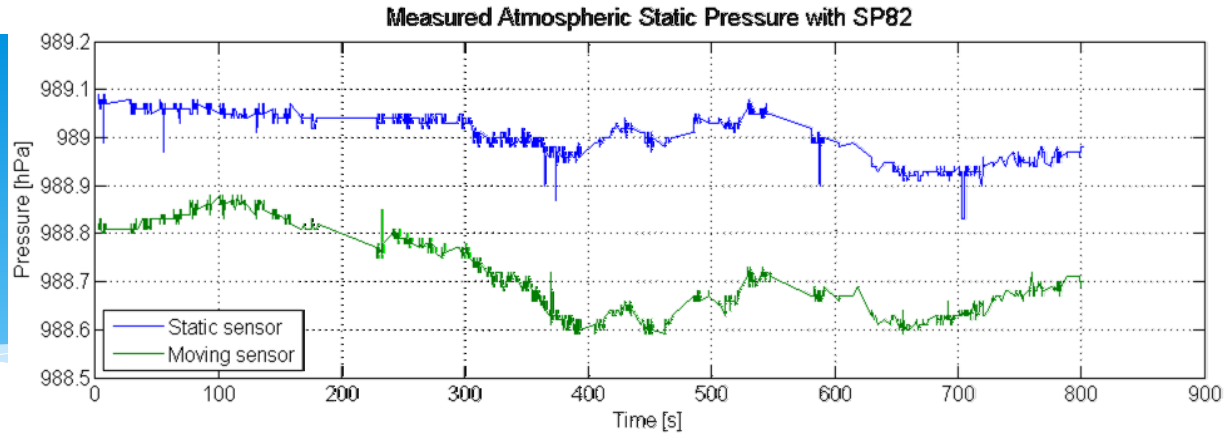


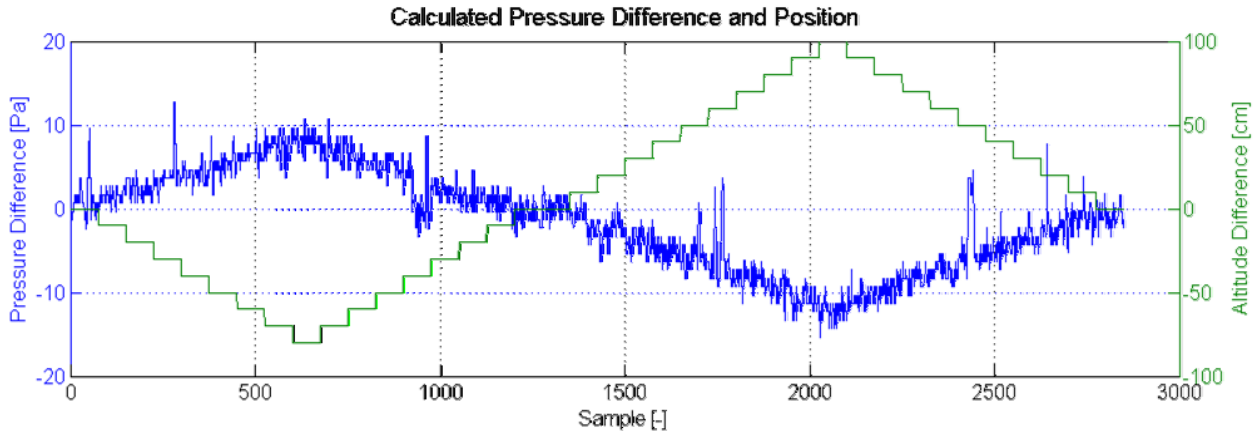
Aktivity

* Bezdrátová platforma pro přenos dat
  * SSP, 3D box, SP82box – sonda
  * Celkem 11 lab. Úloh
  * Idea z NASA Ames Research Center
* Několik prezentací v zahraničí
* Nový systém pro měření polohových úhlů
  * Přesnost 1° dlouhodobě
  * Letové testy







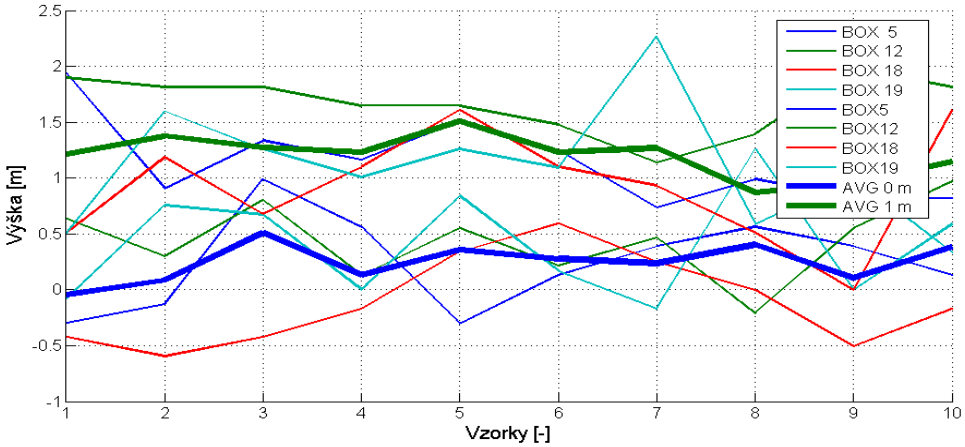


Realizace

* Dva absolutní senzory
* Dva objemy

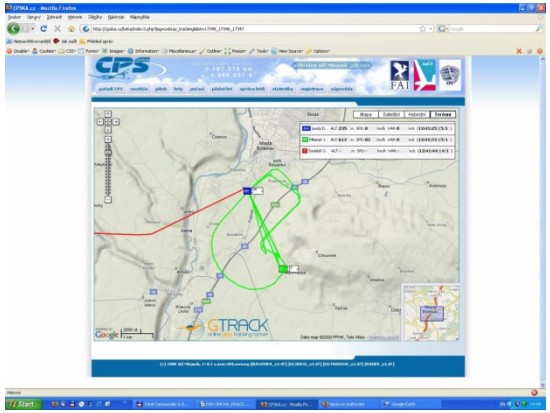
Testy

* Laboratoř
* Tunel

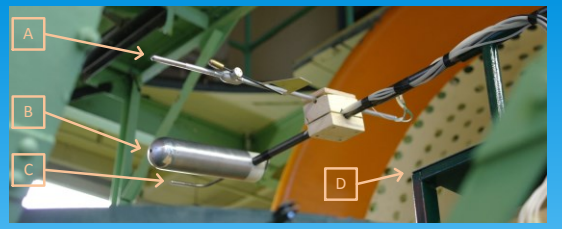


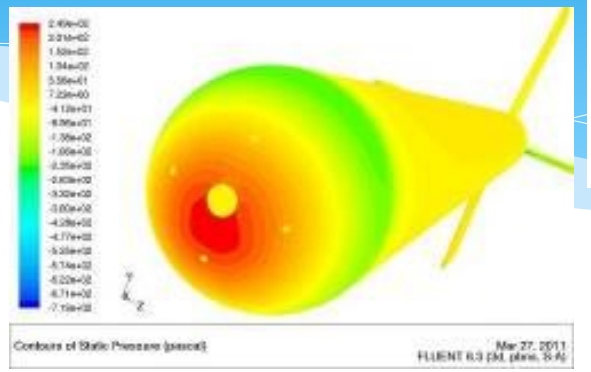
Sledování letadel

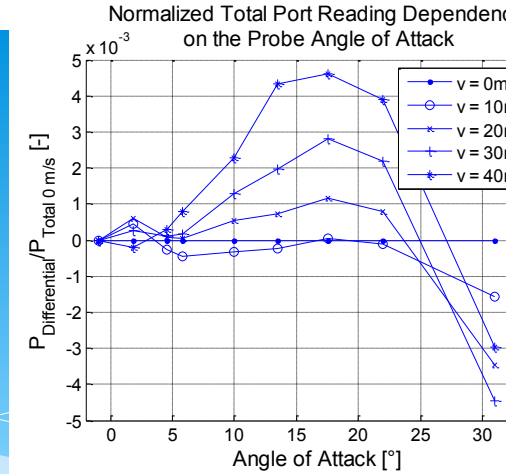
* Vyhodnocení průběhu plachrařských soutěží
* Jak vyhrát?



Další projekty







* Letní stáže
* Bak. a diplomové práce
* Ph.D. studium