Sensor Fusion

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What is Sensor Fusion?

- Combination of different types of sensors to reach a better performance than possible with a single sensor

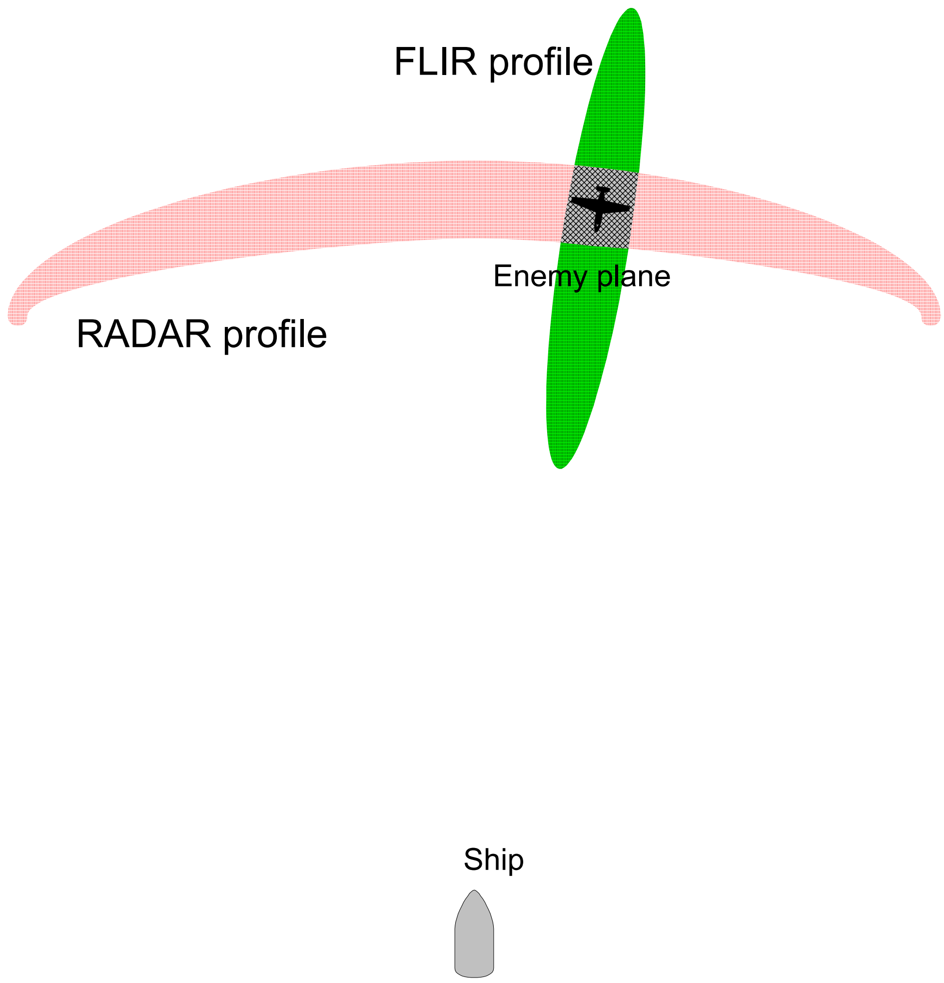
- Best sensor fusion system: The human brain

Why use it?

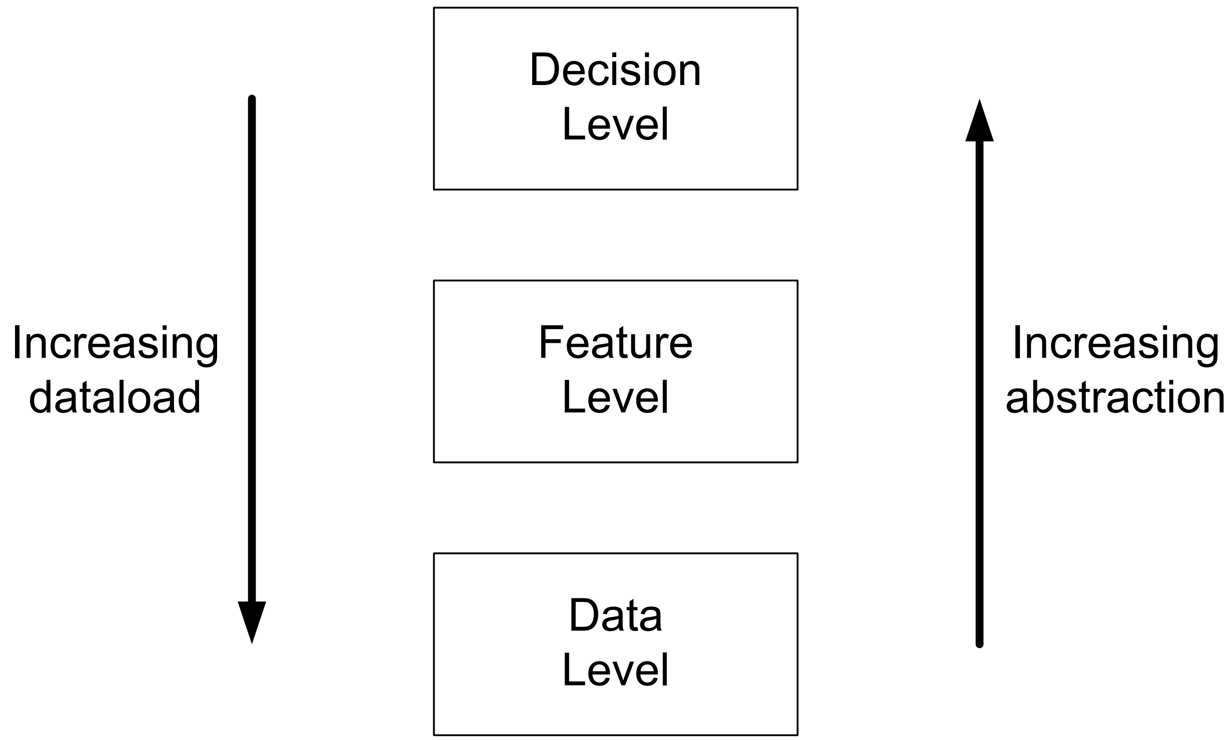
- To achieve better performance
- Extra sensors could work as backup if others fail (redundancy)

Complementary Sensors

Example:



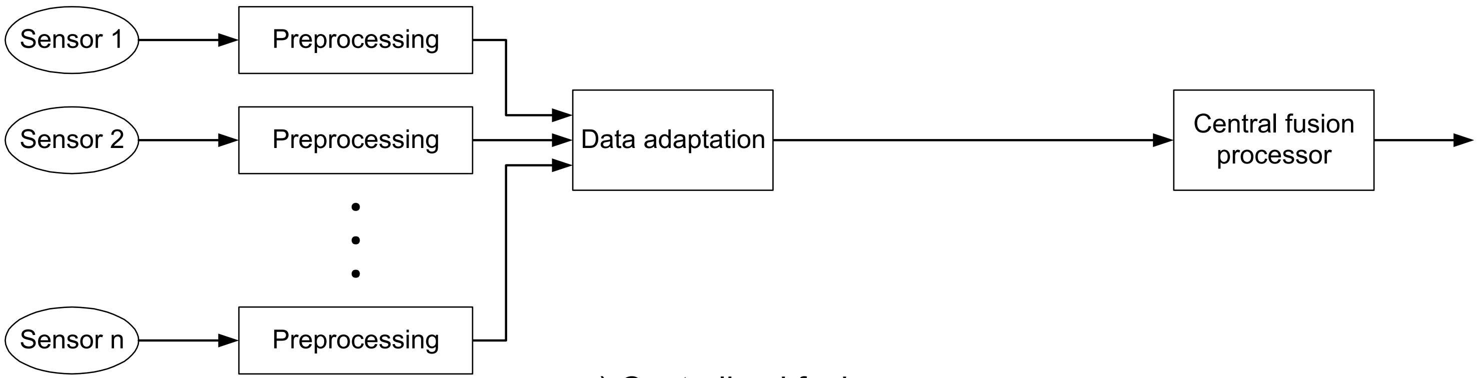
Fusion Levels



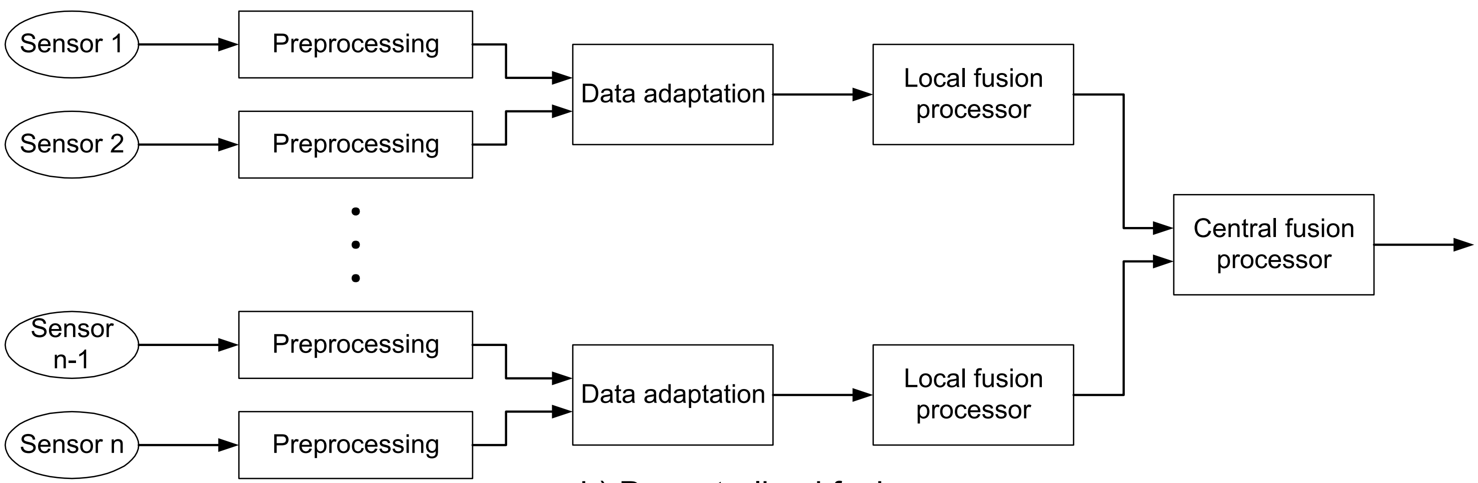
Applied Techniques

Fusion Level	Function	Techniques
Data Level	Spectral Datamining	Digital Signal Processing
	Data Adaptation	Coordinate Transforms Unit Adjustments
	Estimation of Parameters	Kalman Filtering Batch Estimation
Feature Level	Classification	Pattern Recognition Fuzzy Logic Neural Networks
Decision Level	Decide Action	Expert Systems Artificial Intelligence

Decentralized Fusion

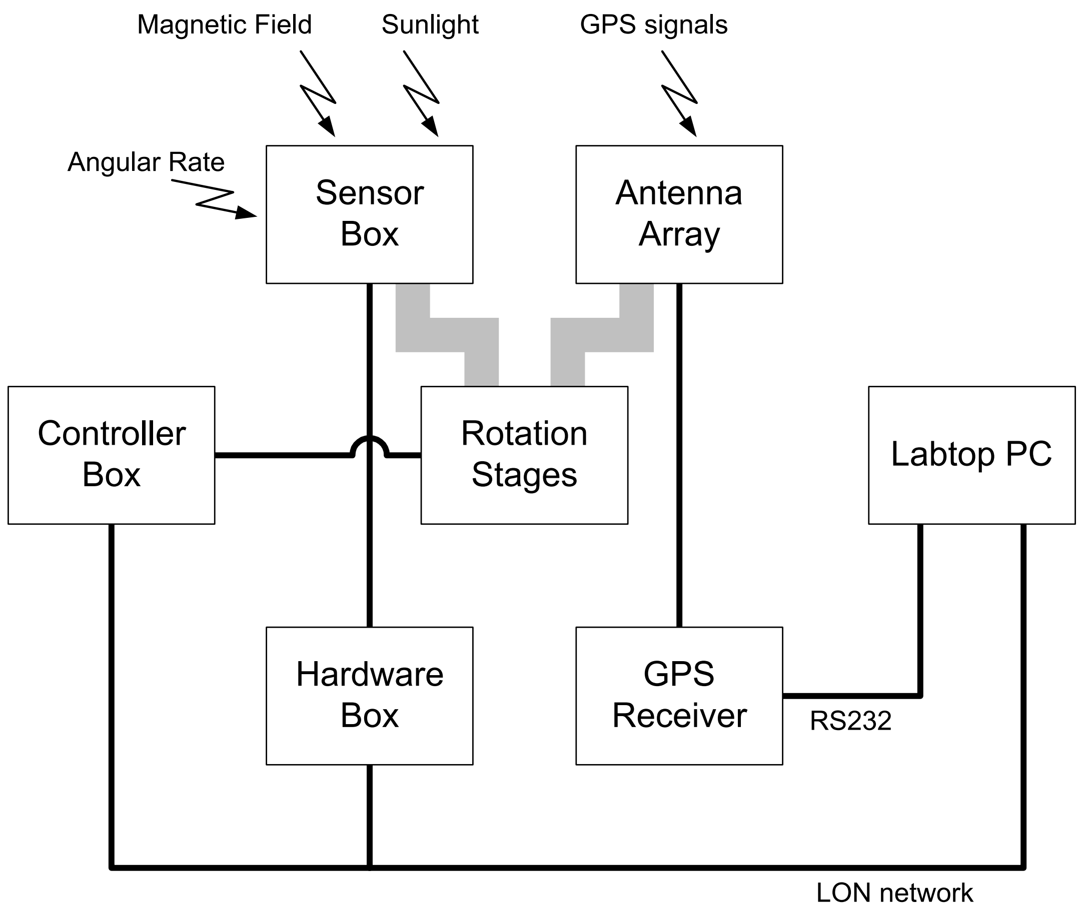


a) Centralized fusion



b) Decentralized fusion

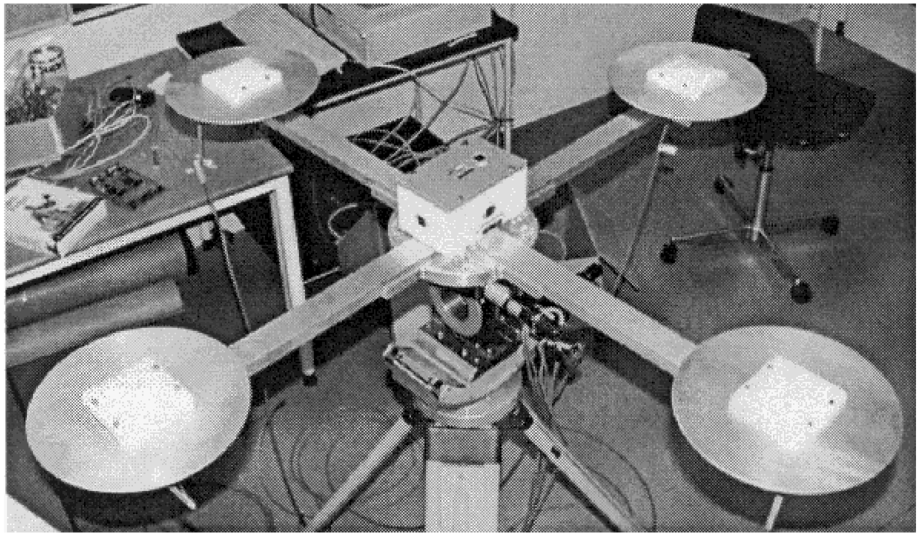
Extra Sensors

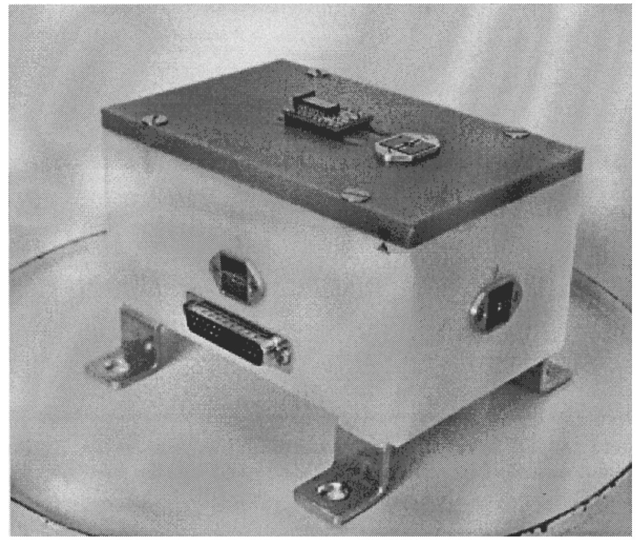


- **Solar Sensor**
- **Magnetometer**
- **Rate Gyros**

+ GPS

The Upgraded Testbed





Vector Matching

Wahba's Problem:

$$minimize \qquad J(\mathbf{A}) = \sum_{i=1}^{n} ||\mathbf{v}_i^B - \mathbf{A}\mathbf{v}_i^R||^2$$

Solution: Use the SVD method

1. Form B matrix of outer products

$$\mathbf{B} = \sum_{i=1}^{n} \mathbf{v}_i^B (\mathbf{v}_i^R)^T$$

Vector Matching

2. Split B into three matrices using Singular Value Decomposition

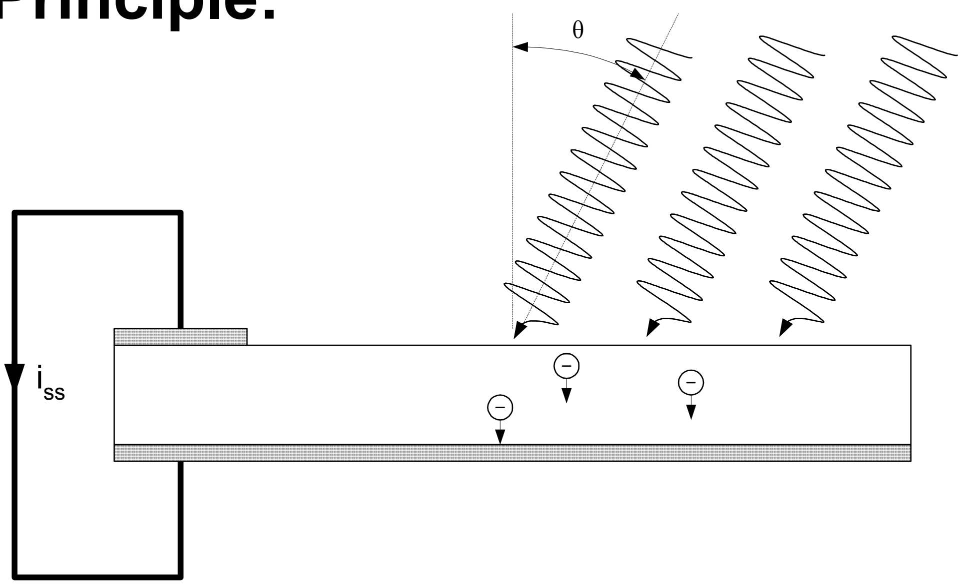
$$\mathbf{B} = \mathbf{U}\,\mathbf{S}\,\mathbf{V}^T$$

3. The optimal attitude matrix best fitting the vector pairs can be found as:

$$\mathbf{A}_{opt} = \mathbf{U}\,diag[1\ \ 1\ \ (\det\mathbf{U})(\det\mathbf{V})]\,\mathbf{V}^T$$

Solar Cells

Working Principle:

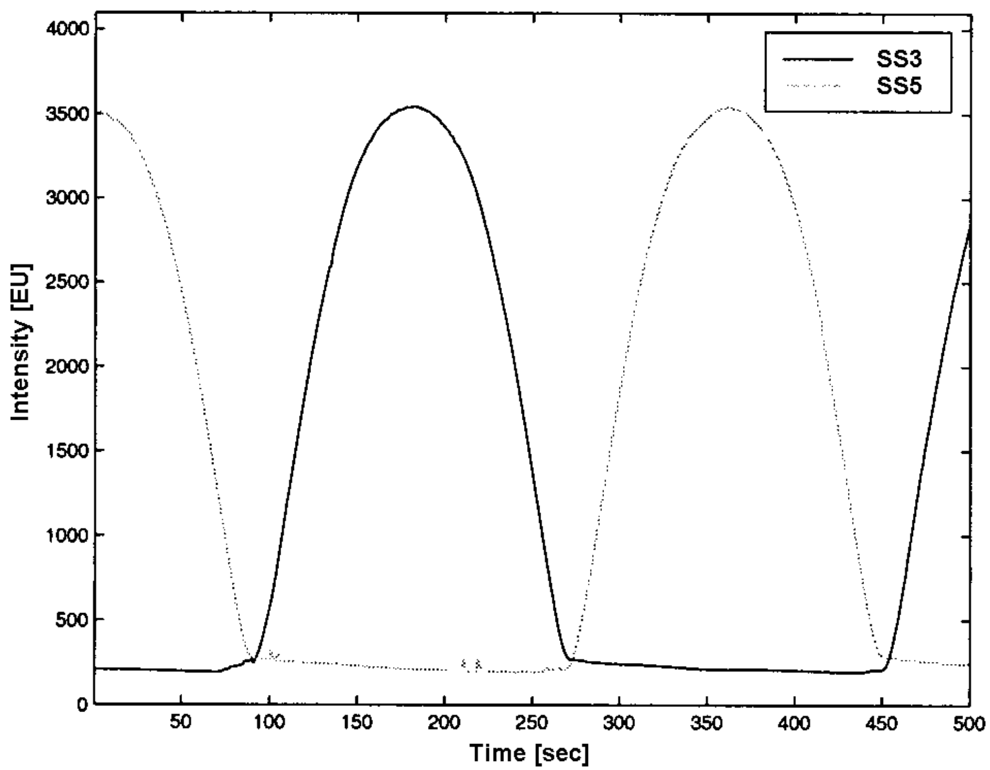


Model:

$$i_{sc} = i_{max} \cos\theta + v_s$$

Solar Cells

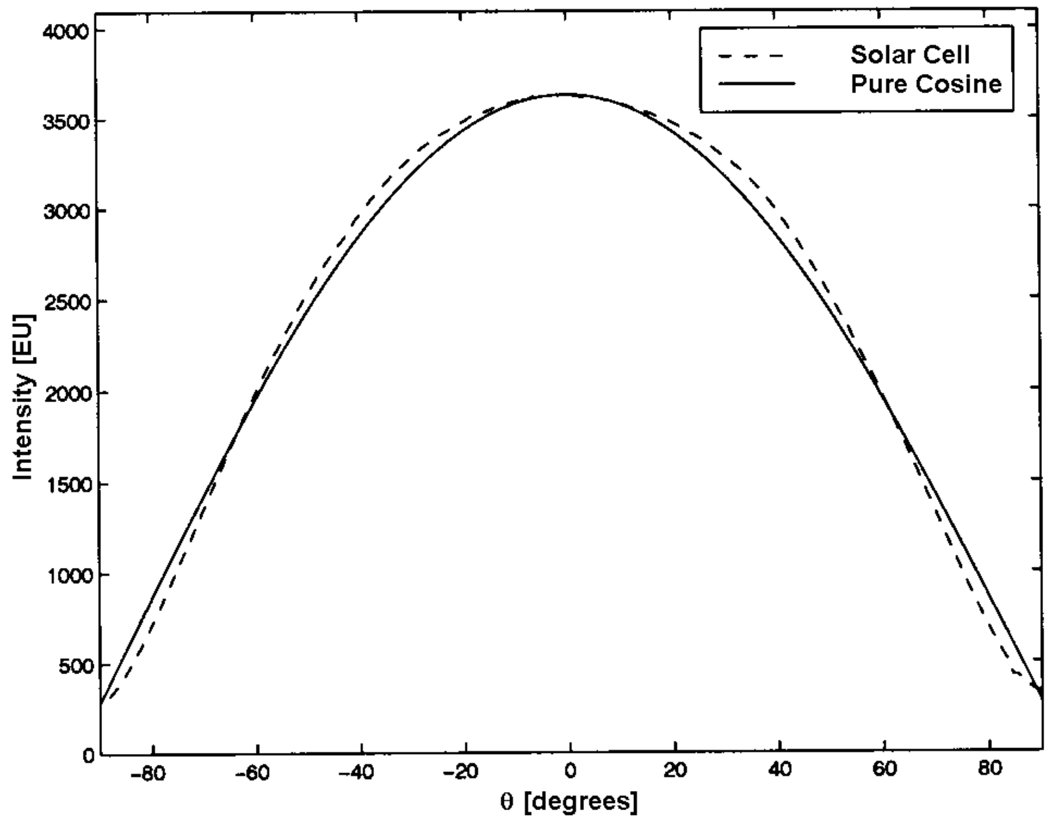
Temperature effects



Solar Cells

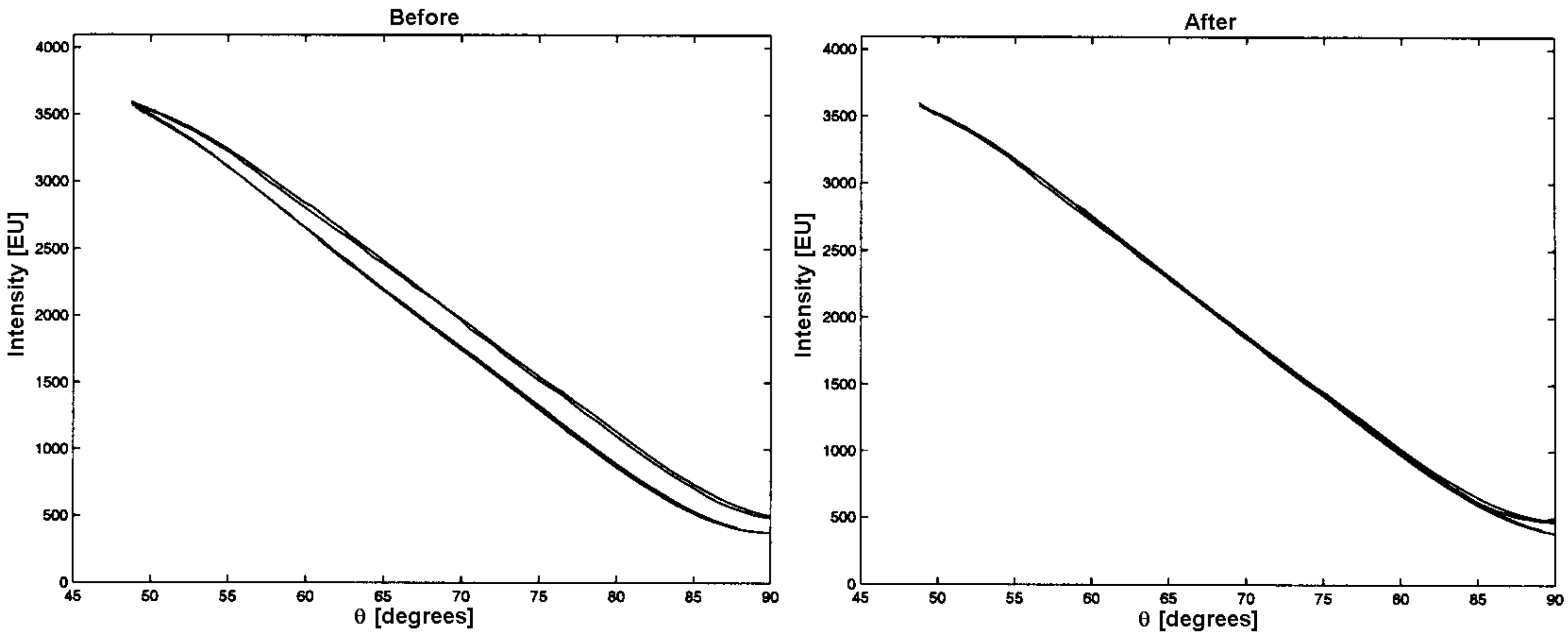
Calibration

- Sensitivity
- Mounting
- Cosine char.



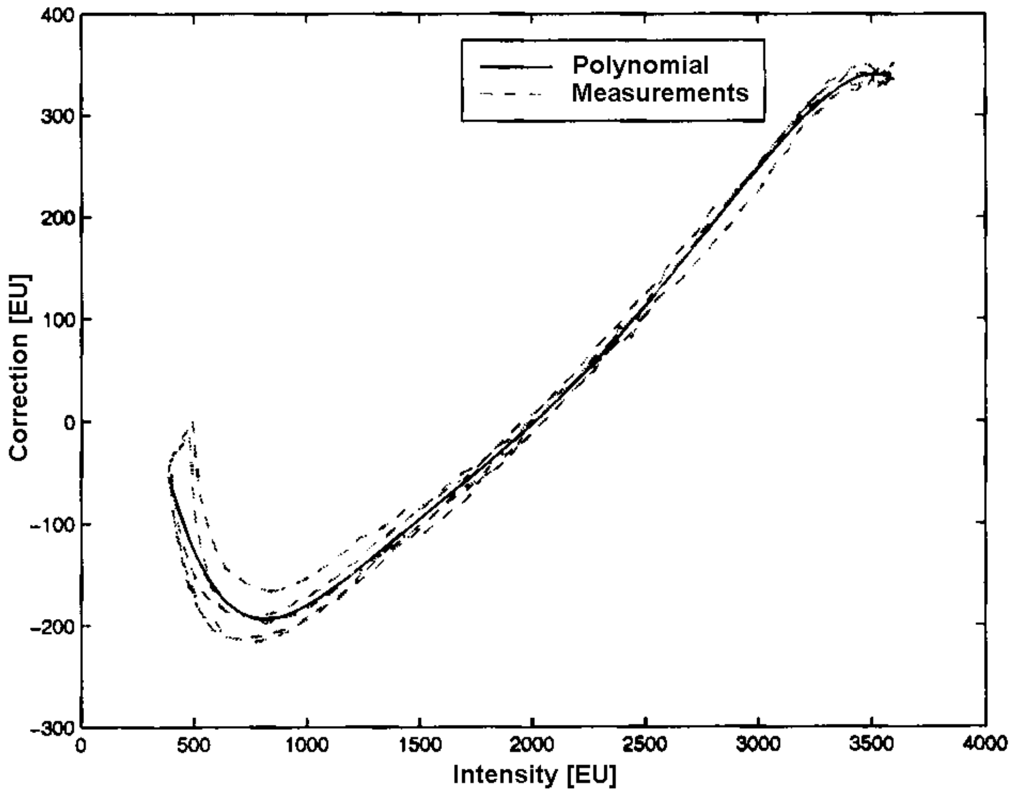
Solar Cells

Mounting errors (adjustment of cell-axis)



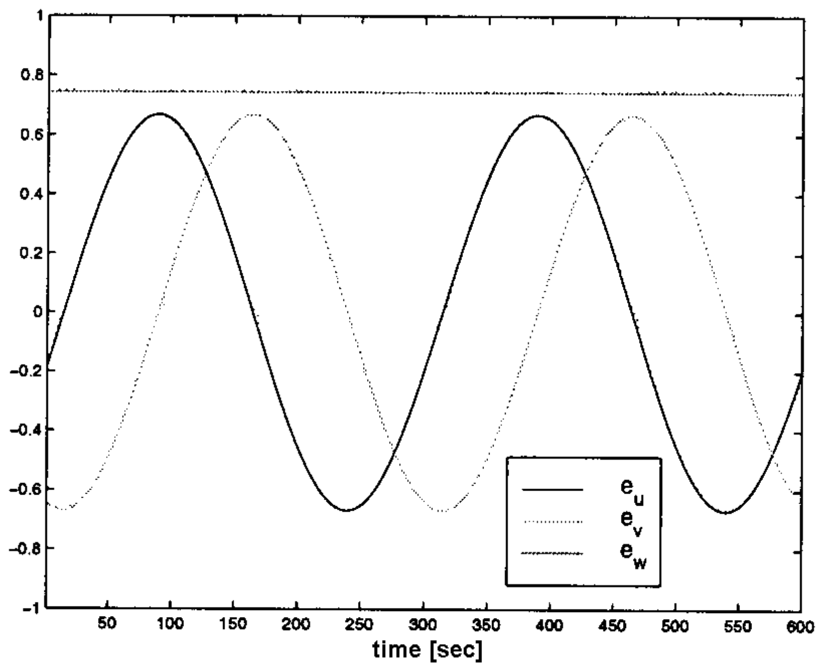
Solar Cells

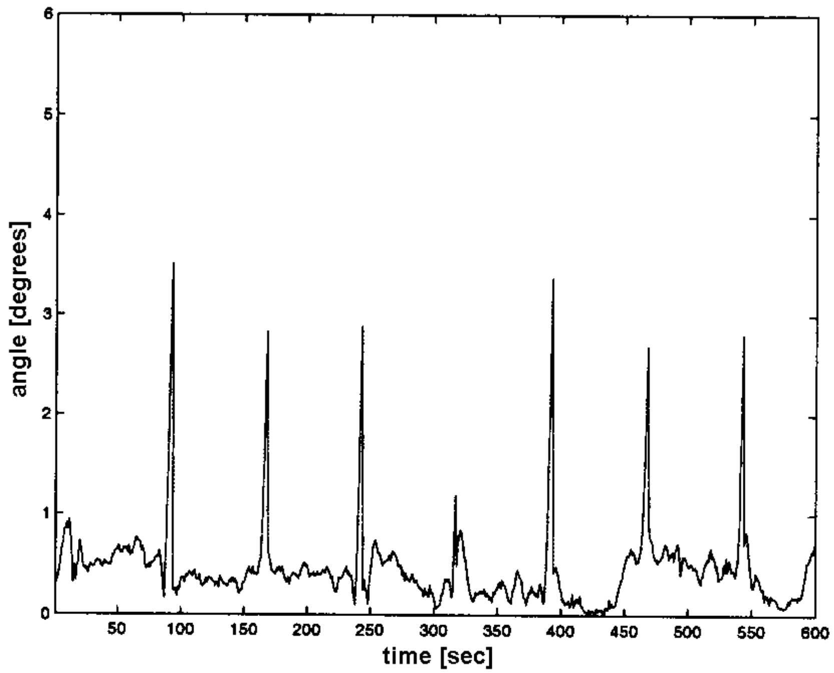
Cosine corrections



Sun Sensor

Performance



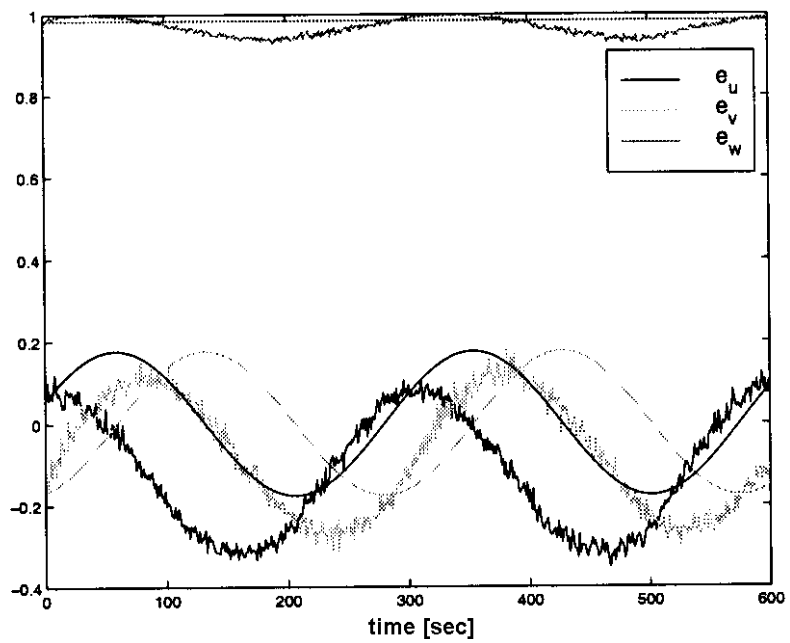


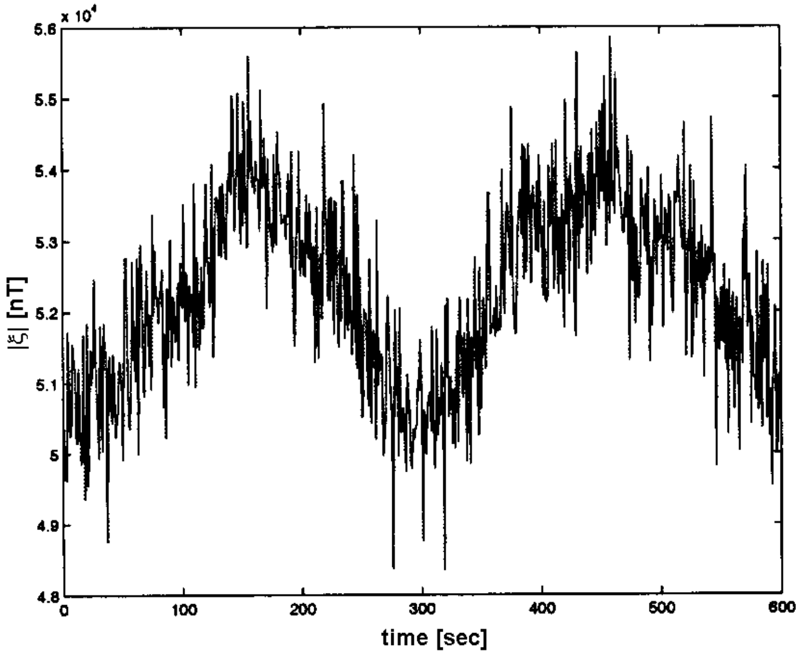
White Noise?

Magnetometer

Calibration

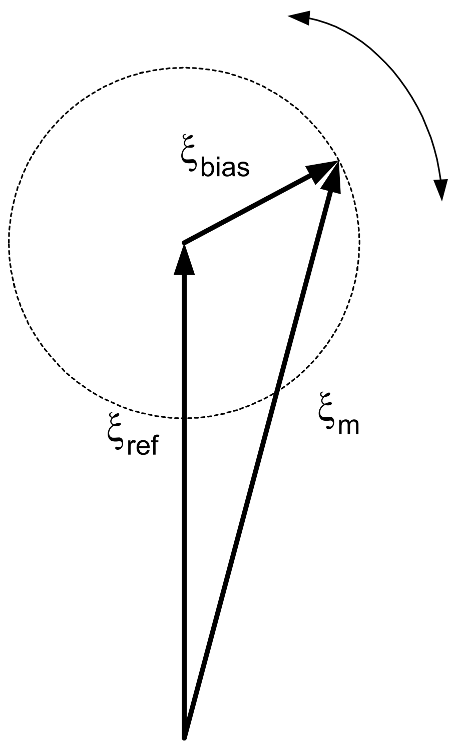
- Field bias
- Mounting uncertainties





Magnetometer

Calculating internal bias



At 'zero' attitude (A = I)

$$\xi_{ref} = \xi_o + \xi_{bias}$$

Each measurement

$$\xi_m = \mathbf{A}\,\xi_o + \xi_{bias}$$

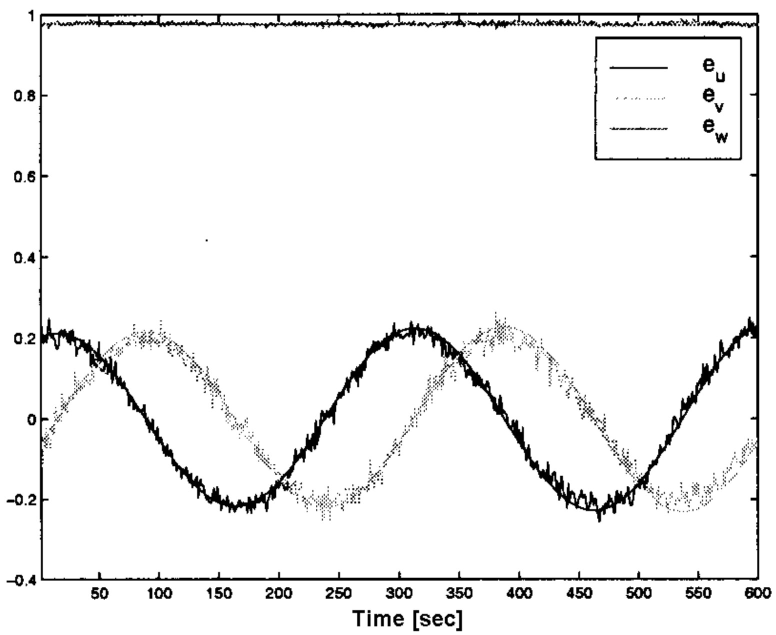
Least Square

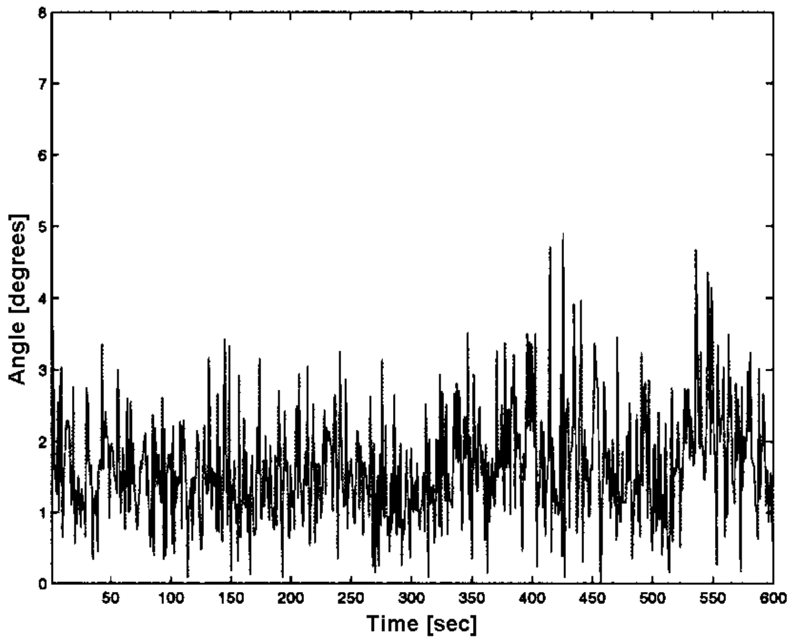
$$\begin{aligned} \xi_m &= \mathbf{A}\,\xi_o + (\xi_{ref} - \xi_o) \\ \xi_m - \xi_{ref} &= (\mathbf{A} - \mathbf{I})\xi_o \end{aligned}$$

Magnetometer

Mounting uncertainties calibrated by a small rotation, found using the SVD method

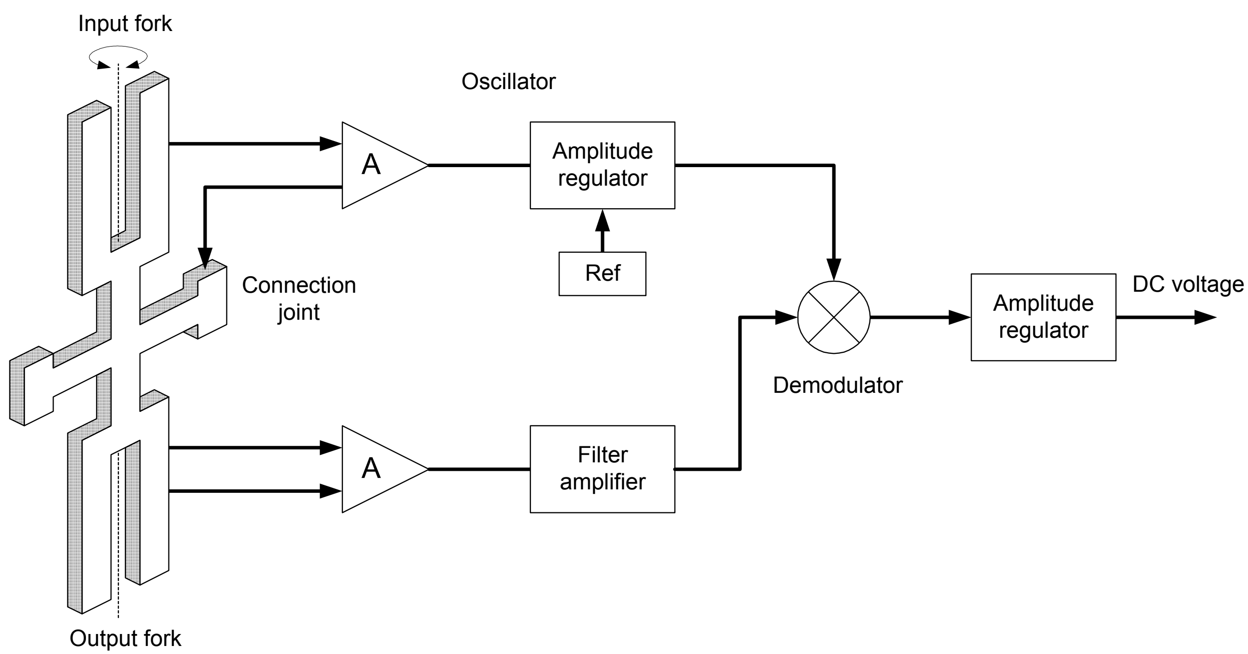
Result:





Rate Gyros

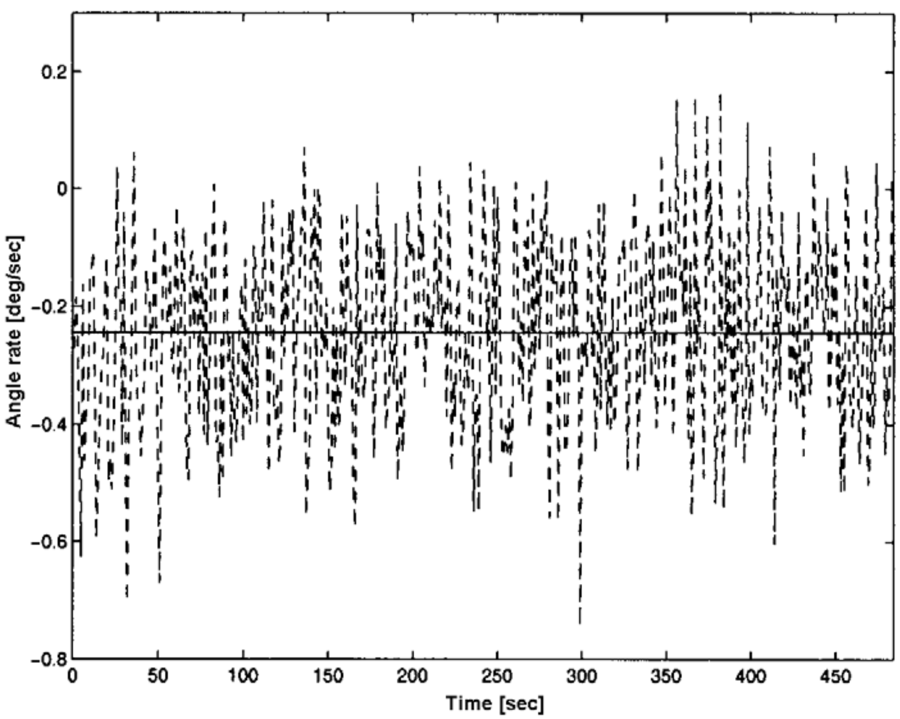
Working Principle:



Measures the state (angular rate) directly

Rate Gyros

Error sources:



- **Noise**
- **Timevar. bias**
- **Scalefactor**
- **Accel. sensitivity**
- **Off-axis error**

Data Fusion

Measurement model:

$$\mathbf{x}(t_k) = \begin{bmatrix} \boldsymbol{q} \\ \boldsymbol{\omega} \\ \boldsymbol{\beta} \\ \boldsymbol{\beta}_r \end{bmatrix} \qquad \mathbf{z}(t_k) = \begin{bmatrix} \Delta\varphi_{11} \\ \Delta\varphi_{12} \\ \Delta\varphi_{13} \\ \vdots \\ \Delta\varphi_{N1} \\ \Delta\varphi_{N2} \\ \Delta\varphi_{N3} \\ \nu_2 \\ \nu_3 \\ \mathbf{e}_m^B \\ \mathbf{e}_s^B \end{bmatrix} \qquad \mathbf{h}[\mathbf{x}(t_k), t_k] = \begin{bmatrix} \mathbf{b}_1^T\mathbf{A}\mathbf{e}_1^R + \beta_1 \\ \mathbf{b}_1^T\mathbf{A}\mathbf{e}_1^R + \beta_2 \\ \mathbf{b}_1^T\mathbf{A}\mathbf{e}_1^R + \beta_3 \\ \vdots \\ \mathbf{b}_1^T\mathbf{A}\mathbf{e}_N^R + \beta_1 \\ \mathbf{b}_1^T\mathbf{A}\mathbf{e}_N^R + \beta_2 \\ \mathbf{b}_1^T\mathbf{A}\mathbf{e}_N^R + \beta_3 \\ \omega_2 + \beta_{r2} \\ \omega_3 + \beta_{r3} \\ \mathbf{A}\mathbf{e}_m^R \\ \mathbf{A}\mathbf{e}_s^R \end{bmatrix}$$

Data Fusion

Measurement gradient matrix:

$$\mathbf{H}[\mathbf{x}(t_k), t_k] = \begin{bmatrix} -2(\mathbf{A}\mathbf{e}_1^R)^T\mathbf{B}_1^\times & & & \\ -2(\mathbf{A}\mathbf{e}_1^R)^T\mathbf{B}_2^\times & \mathbf{0}_{3\times 3} & \mathbf{1}_{3\times 3} & \mathbf{0}_{3\times 2} \\ -2(\mathbf{A}\mathbf{e}_1^R)^T\mathbf{B}_3^\times & & & \\ \vdots & \vdots & \vdots & \vdots \\ -2(\mathbf{A}\mathbf{e}_N^R)^T\mathbf{B}_1^\times & & & \\ -2(\mathbf{A}\mathbf{e}_N^R)^T\mathbf{B}_2^\times & \mathbf{0}_{3\times 3} & \mathbf{1}_{3\times 3} & \mathbf{0}_{3\times 2} \\ -2(\mathbf{A}\mathbf{e}_N^R)^T\mathbf{B}_3^\times & & & \\ 0 \quad 0 \quad 0 & 0 \quad 1 \quad 0 & 0 \quad 0 \quad 0 & 1 \quad 0 \\ 0 \quad 0 \quad 0 & 0 \quad 0 \quad 1 & 0 \quad 0 \quad 0 & 0 \quad 1 \\ 2(\mathbf{A}\mathbf{e}_m^R)^\times & \mathbf{0}_{3\times 3} & \mathbf{0}_{3\times 3} & \mathbf{0}_{3\times 2} \\ 2(\mathbf{A}\mathbf{e}_s^R)^\times & \mathbf{0}_{3\times 3} & \mathbf{0}_{3\times 3} & \mathbf{0}_{3\times 2} \end{bmatrix}$$

State Fusion

Using receiver solution as input measurement

$$\mathbf{z}_q(t_k) = \begin{bmatrix} \hat{q}_1 \\ \hat{q}_2 \\ \hat{q}_3 \\ \hat{q}_4 \end{bmatrix} \qquad \mathbf{h}[\mathbf{x}(t_k), t_k] = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \qquad \mathbf{H}_q[\mathbf{x}(t_k), t_k] = \begin{bmatrix} \mathbf{1}_{3\times 3} & \mathbf{0}_{3\times 3} \\ \mathbf{0}_{3\times 3} & \mathbf{0}_{3\times 3} \end{bmatrix}$$

Residuals must be redefined:

$$\begin{aligned} \delta\mathbf{x}(t_k) &\neq \mathbf{K}(\mathbf{z}_q(t_k) - \mathbf{h}_q[\mathbf{x}(t_k), t_k]) \\ &\Downarrow \\ \delta\mathbf{x}(t_k) &= \mathbf{K}(\mathbf{z}_q(t_k) \otimes \mathbf{h}_q[\mathbf{x}(t_k), t_k]^*) \end{aligned}$$

Results

Data fusion

5 Satellites

GPS	GPS + Sun sensor	Improvement
0.33 deg	0.30 deg	9 %

GPS + Magnetometer	Improvement
0.32 deg	3 %

GPS + Rate gyros	Improvement
0.32 deg	3 %

GPS + All	Improvement
0.29 deg	12 %

3 Satellites

GPS	GPS + All	Improvement
0.48 deg	0.38 deg	21 %

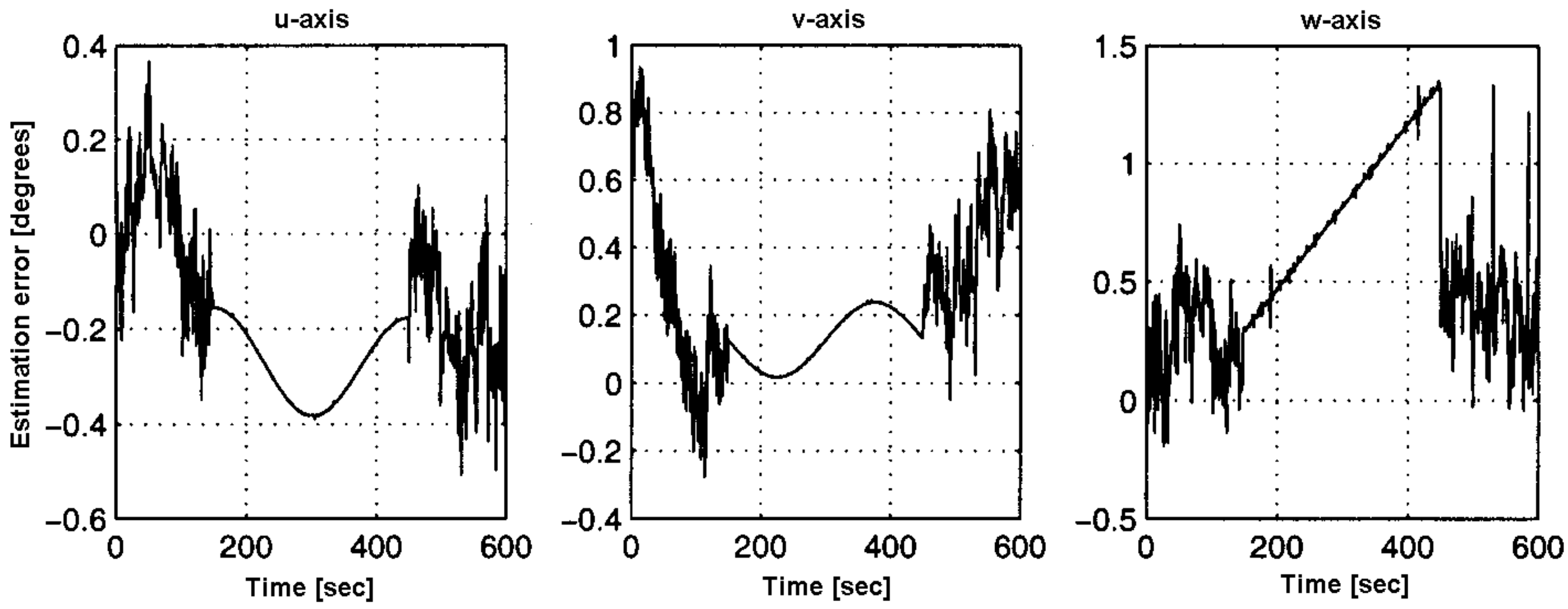
Results

State fusion

Situation	RSS error	MFLOPS
Raw attitude from receiver	0.49 deg	0
Raw attitude from receiver + Kalman	0.42 deg	5.9
Raw attitude from receiver + Kalman + Secondary sensors	0.37 deg	20.2
Phase data from receiver + Kalman	0.33 deg	18.6
Phase data from receiver + Kalman + Secondary sensors	0.29 deg	50.6

Shadowed GPS

	GPS + All secondary	All secondary alone
Pitch (u)	0.13	0.26
Roll (v)	0.17	0.56
Yaw (w)	0.19	0.63
RSS	0.29	0.88



Conclusion

• Sensor fusion techniques can be applied to GPS applications mainly on the data and feature level

• The gain in accuracy was however shown to be only moderate in this project

• Significant error sources include less than optimal sensors and mechanical alignment problems

• The accuracy achieved by secondary sensors alone was shown to be sufficient for many space missions