Sensor Fusion Based Integrated Motion Measurement for Telescope Structures

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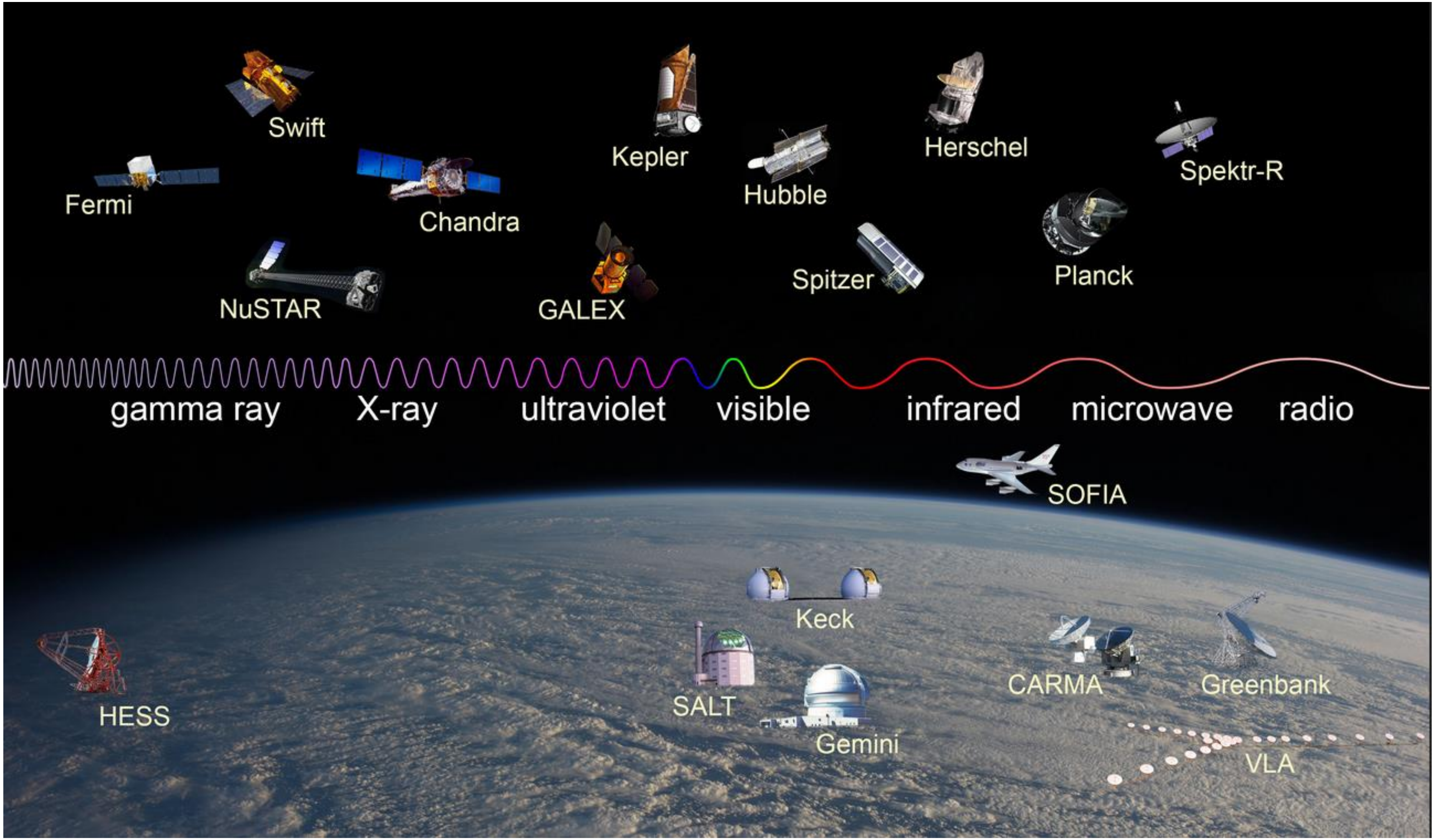
Outline

- Airborne Infrared telescope SOFIA
- Integrated Motion Measurement principle
- Integrated Motion Measurement for SOFIA telescope
- Simulation Results
- Summary

Telescopes and the wavelength



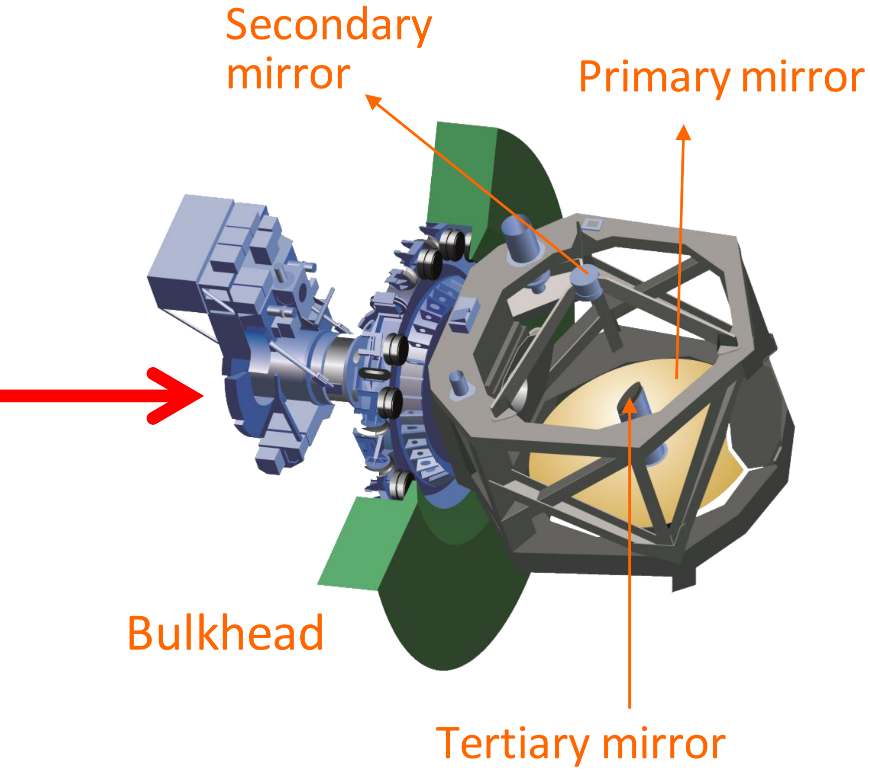
Source: https://www.nasa.gov (2013 status)

Stratospheric Observatory for Infrared Astronomy (SOFIA)

SOFIA is a joint project between NASA and DLR (Germany)

Wavelength: 0.3 to 1600 µm

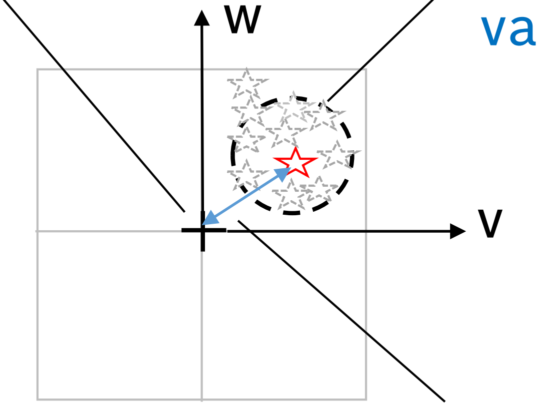
2.7 m Infrared Telescope Structure



Source: *Deutsches SOFIA Institut*

The Telescope assembly (TA)

Combination of the ***Cassegrain*** and the ***Newtonian*** type telescope design

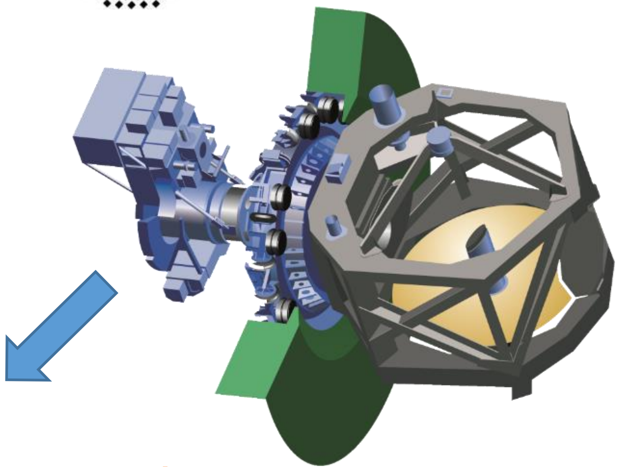


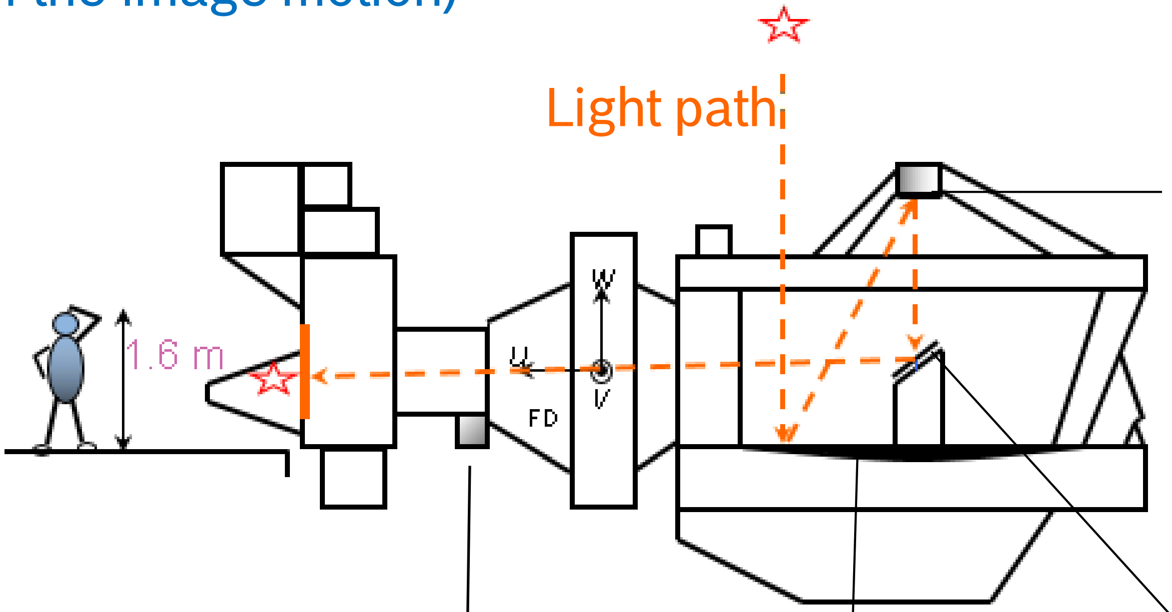
TA boresight

Pointing stability (RMS value of the image motion)

Focal plane

Pointing accuracy





Light path

Secondary mirror

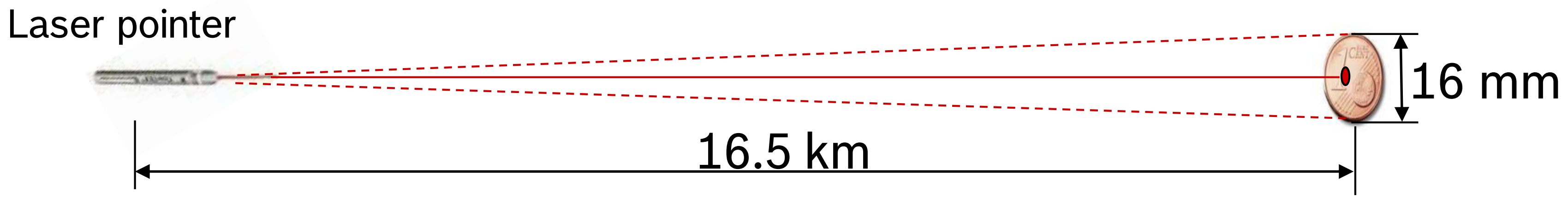
Inertial Measurement Unit (IMU) consists of fiber optic gyroscopes and accelerometers

Primary mirror (**2.7 m**)

Tertiary mirror

	Goal
Pointing stability	0.2 arcsec
Pointing accuracy	0.4 arcsec

SOFIA‘s Pointing Stability goal→ 0.2 arcsec



- Aeroacoustic energy in the cavity causes random vibration in the telescope
- Vibration causes image jitter and therefore affects the pointing stability
- The flexible modes in the bandwidth of 20 to 100 Hz are crucial and identified as the largest contributors to image jitter
- Active reduction of image jitter requires the integrated measurement of the telescope motion in modal coordinates

Power spectral density of Jitter measurement
(wide band response to multi-axial excitation)

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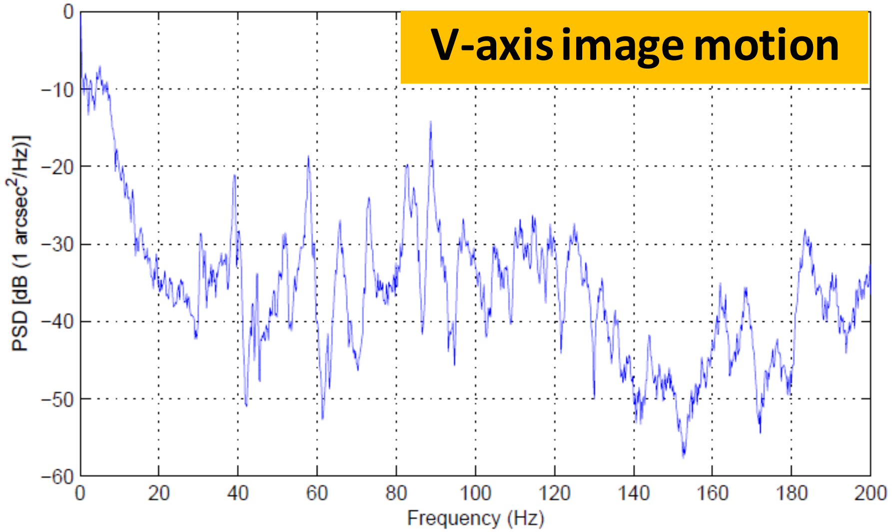
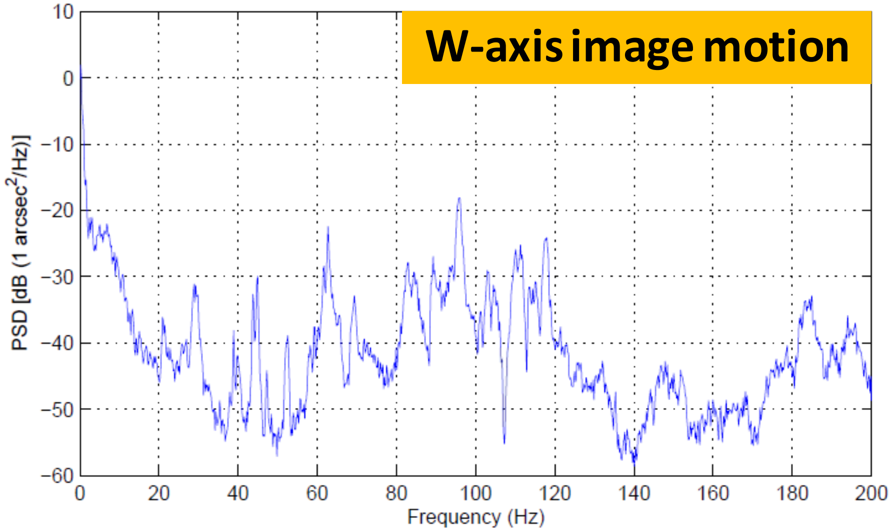
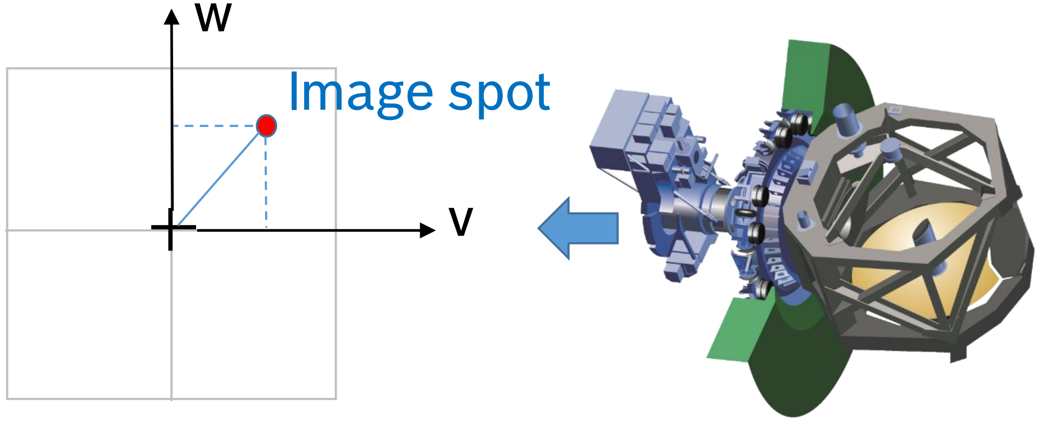




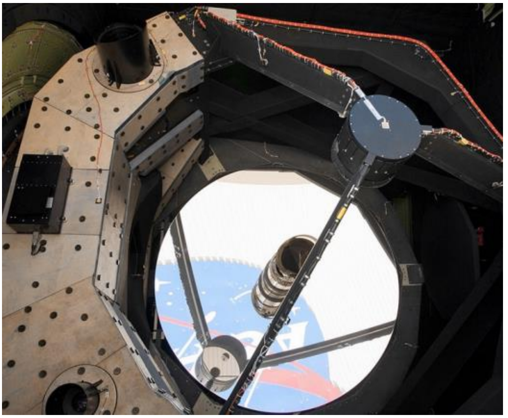


Focal plane

- PSDs of Image motion measurement at the focal plane show the wide band responses
- Many resonance frequencies contribute to image motion

Source of PSDs: B. Greiner, Studienarbeit, 2009, Universität Stuttgart

SOFIA infrared telscope→ Size and fundamental frequency



SOFIA

2.5 m Primary

● f ~ 20 Hz

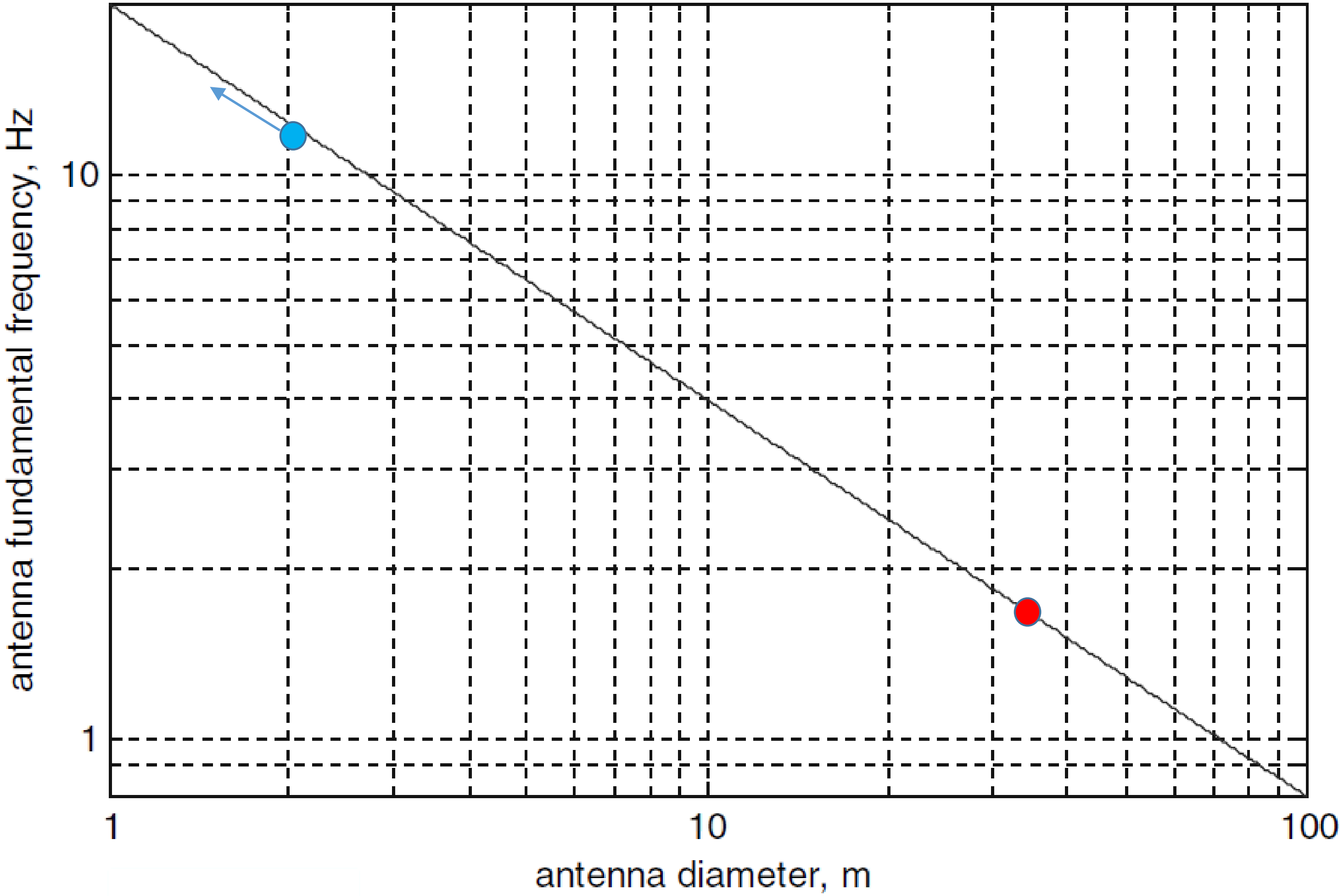
NASA
DSN Antenna – DSS-35

34 m Primary

● f ~ 2 Hz

$$f = 20\, d^{-0.7}$$

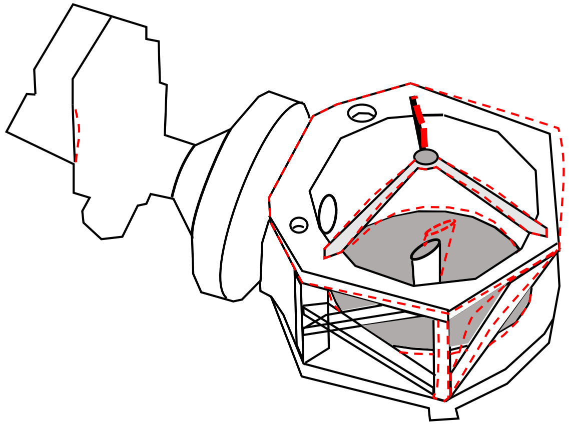
Aerospace Corp. chart



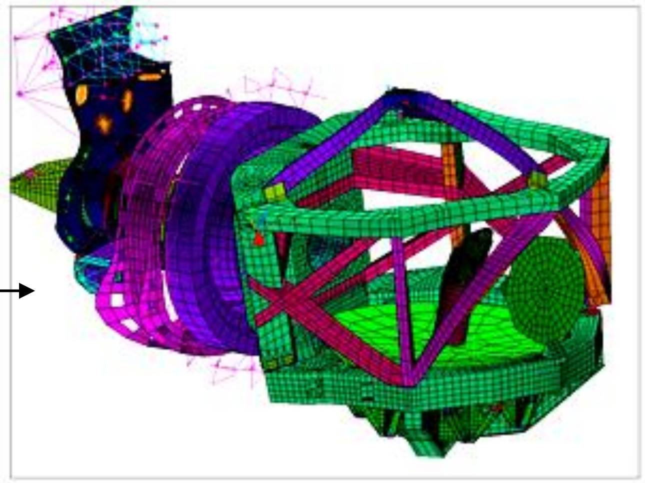
Source: W.Gawronski , Modelling and control of Antennas and Telescopes, Springer, 2008

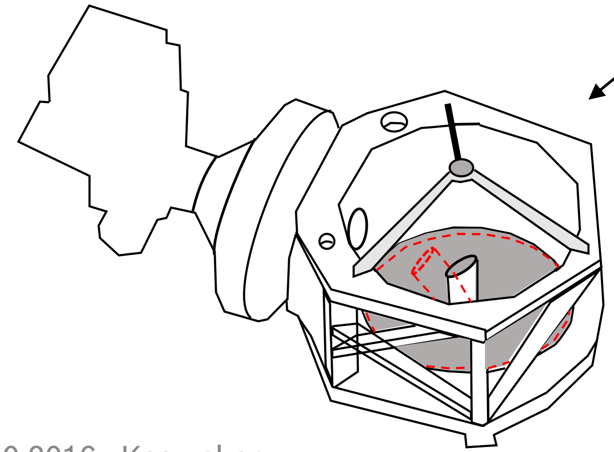
Structural dynamics of the telescope assembly

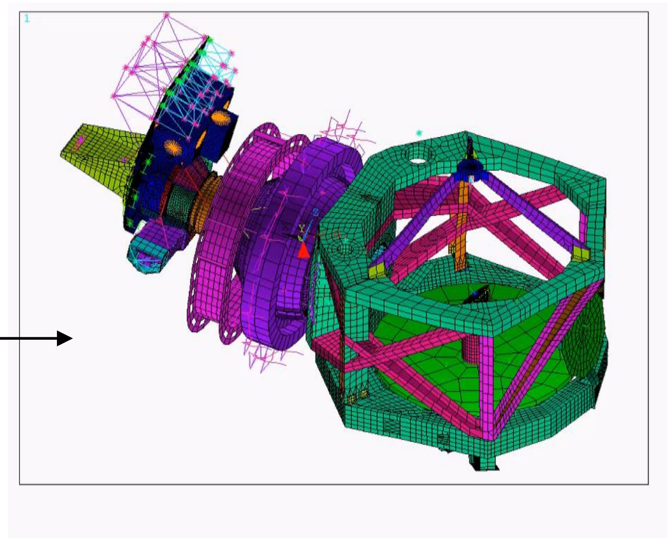
- The telescope structure is modally dense
- Crucial modes identified based on Hankel Singular Values



Crucial vibration modes (Hz)
54.27
72.80
66.63
80.68
93.17
37.65
31.72
106.53
20.53
111.3







Integrated Motion Measurement (IMM)

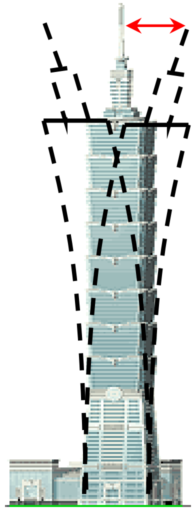
IMM for a flexible structure requires distributed sensors:

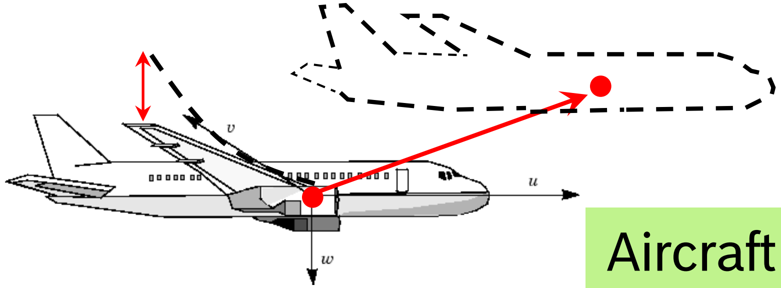
- Local acceleration and/or angular rate measurements
- Distortion measurements (strain gauges, laser sensors, GPS)
- Inertial Measurement Unit (IMU) near Center of Garvity
- A simplified model of the structure

Sensor fusion based system is realised as a state observer

Examples of special cases of IMM:

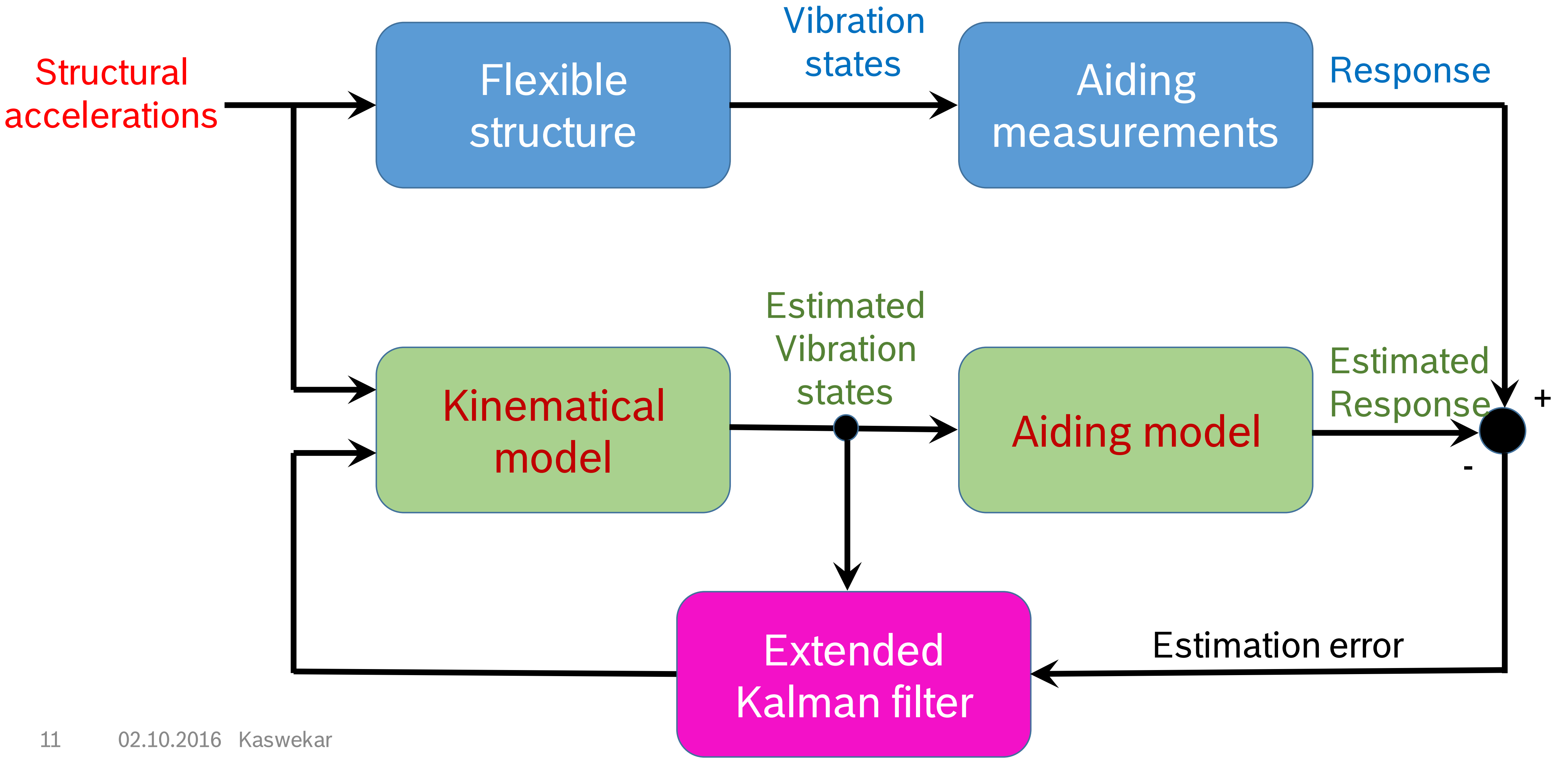
Structural monitoring
(GPS receivers, Strain gauges)



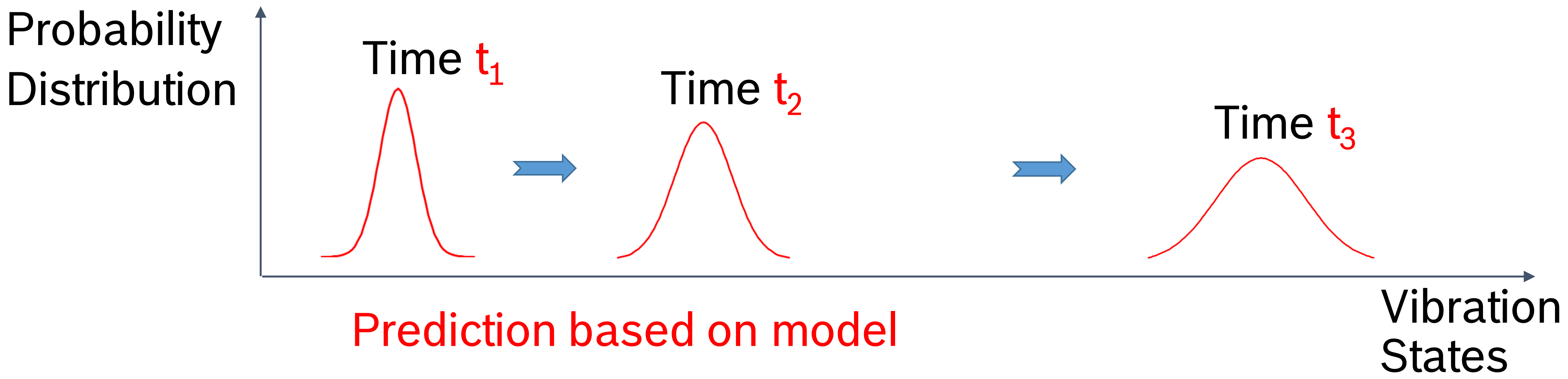


Aircraft guidance and control
(INS, GPS receivers, peripheral accelerometers)

State Observer Principle



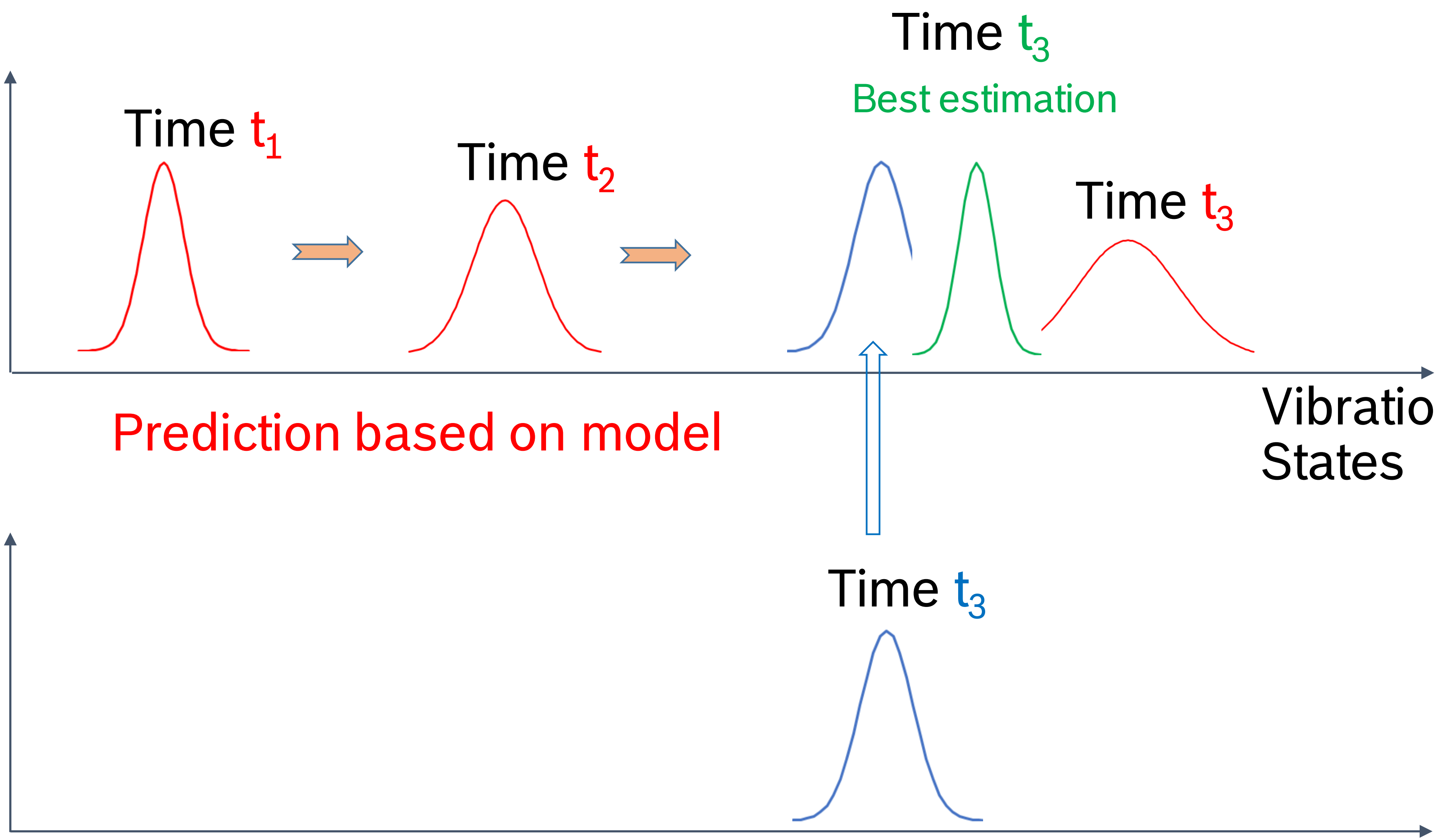
Kalman Filtering



Prediction based on model

Aiding measurements

Kalman Filtering



Probability Distribution

Time t_1

Time t_2

Time t_3

Best estimation

Time t_3

Vibration States

Prediction based on model

Probability Distribution

Time t_3

Vibration States

Aiding measurements

Optimal sensor placements

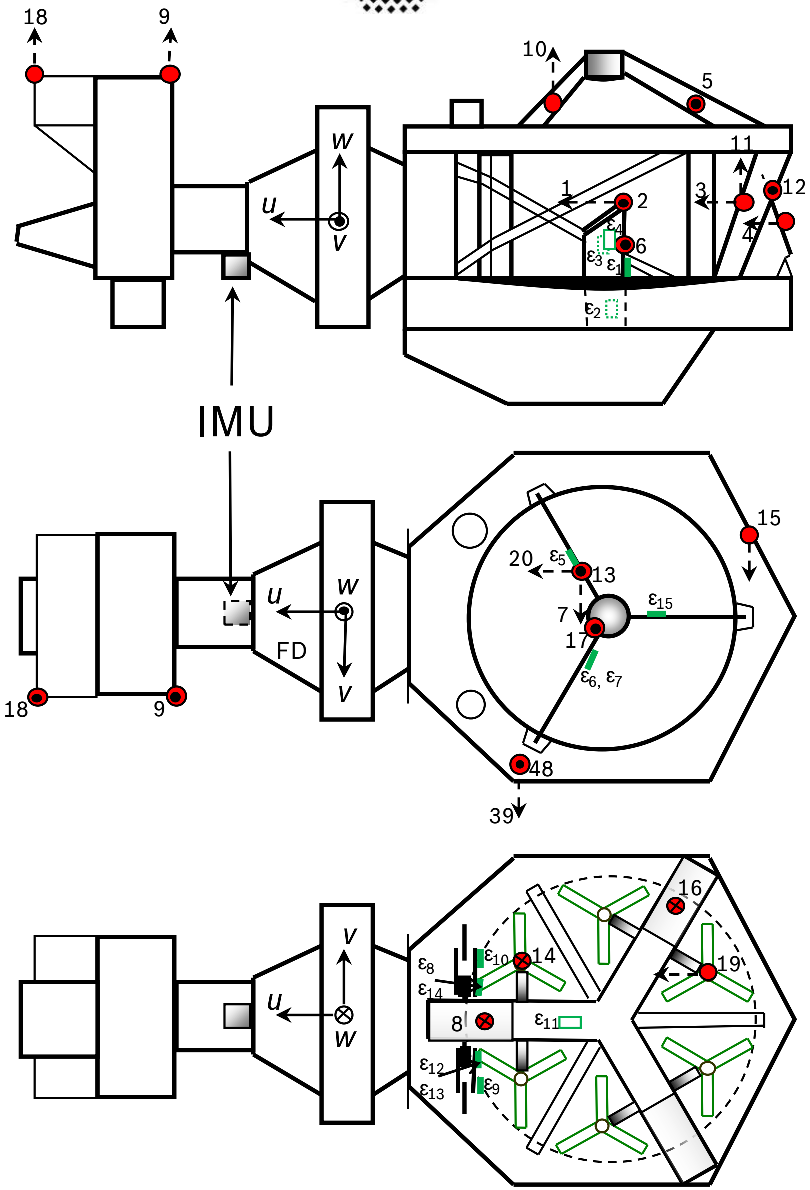
- Simulated measurements with added white noise
- IMU: Fibre Optics Gyroscops + three accelerometers
- Distributed accelerometers : MEMS type
- Aiding measurements: Strain gauges
- Optimal Sensor placement→Hankel Norm based method to search optimal locations

$$\dot{x}_i = A_{mi} x_i + B_{mi} u$$
$$y_i = C_{mi} x_i$$

Hankel Norm

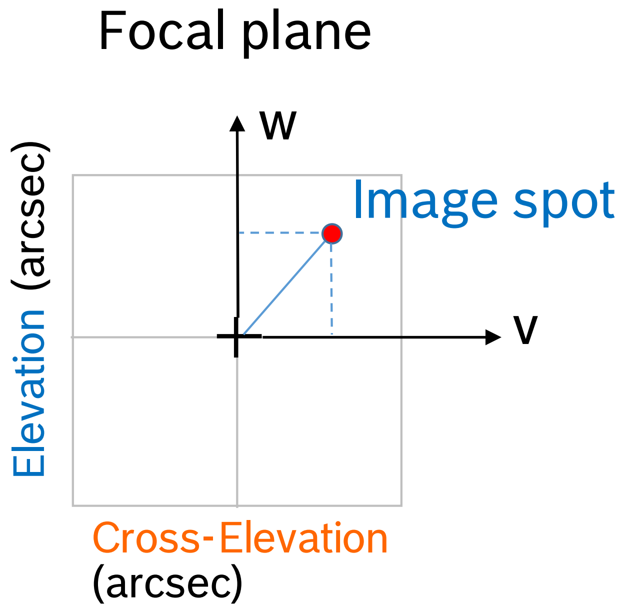
$$\|G_i\|_h \cong \frac{\|B_{mi}\|_2 \, \|C_{mi}\|_2}{4 \zeta_i \omega_i}$$

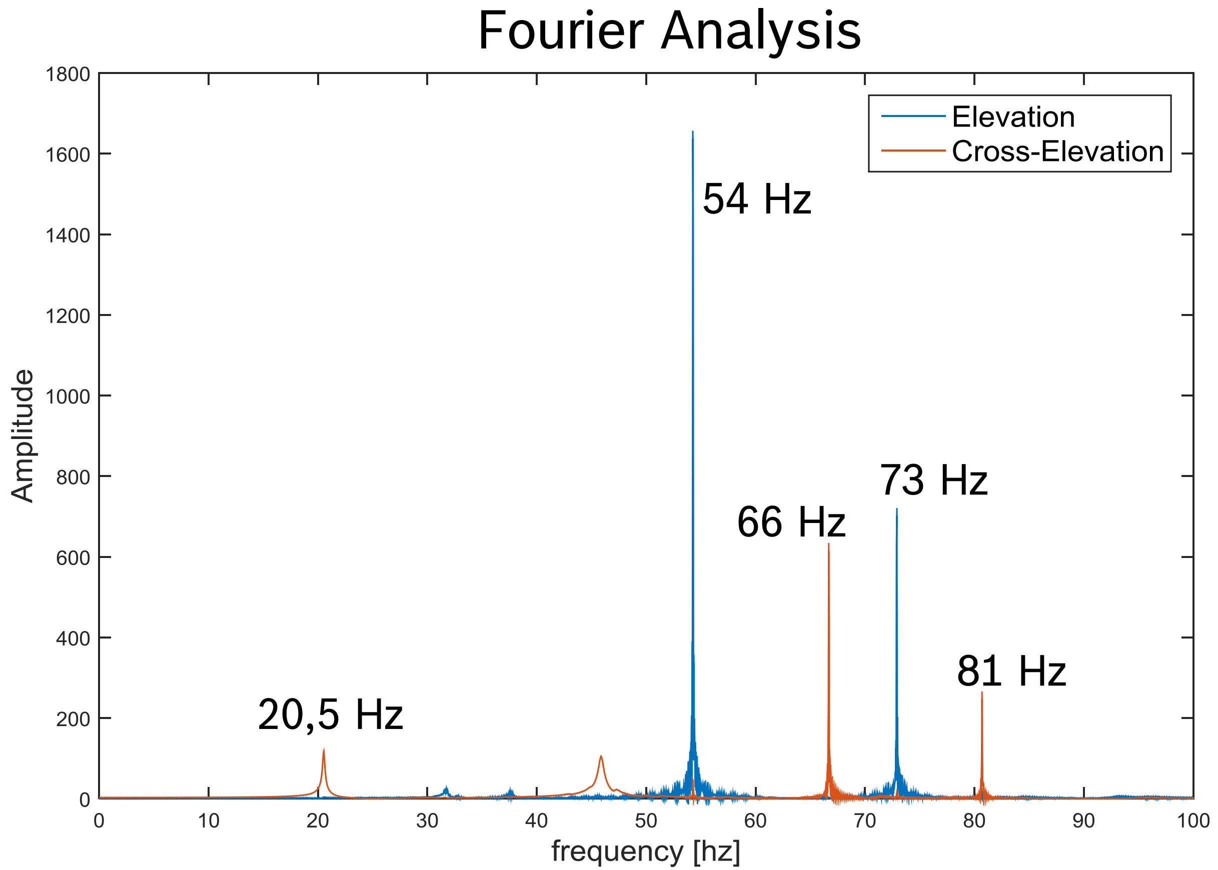
Observability



Optimal locations to target five dominant modes

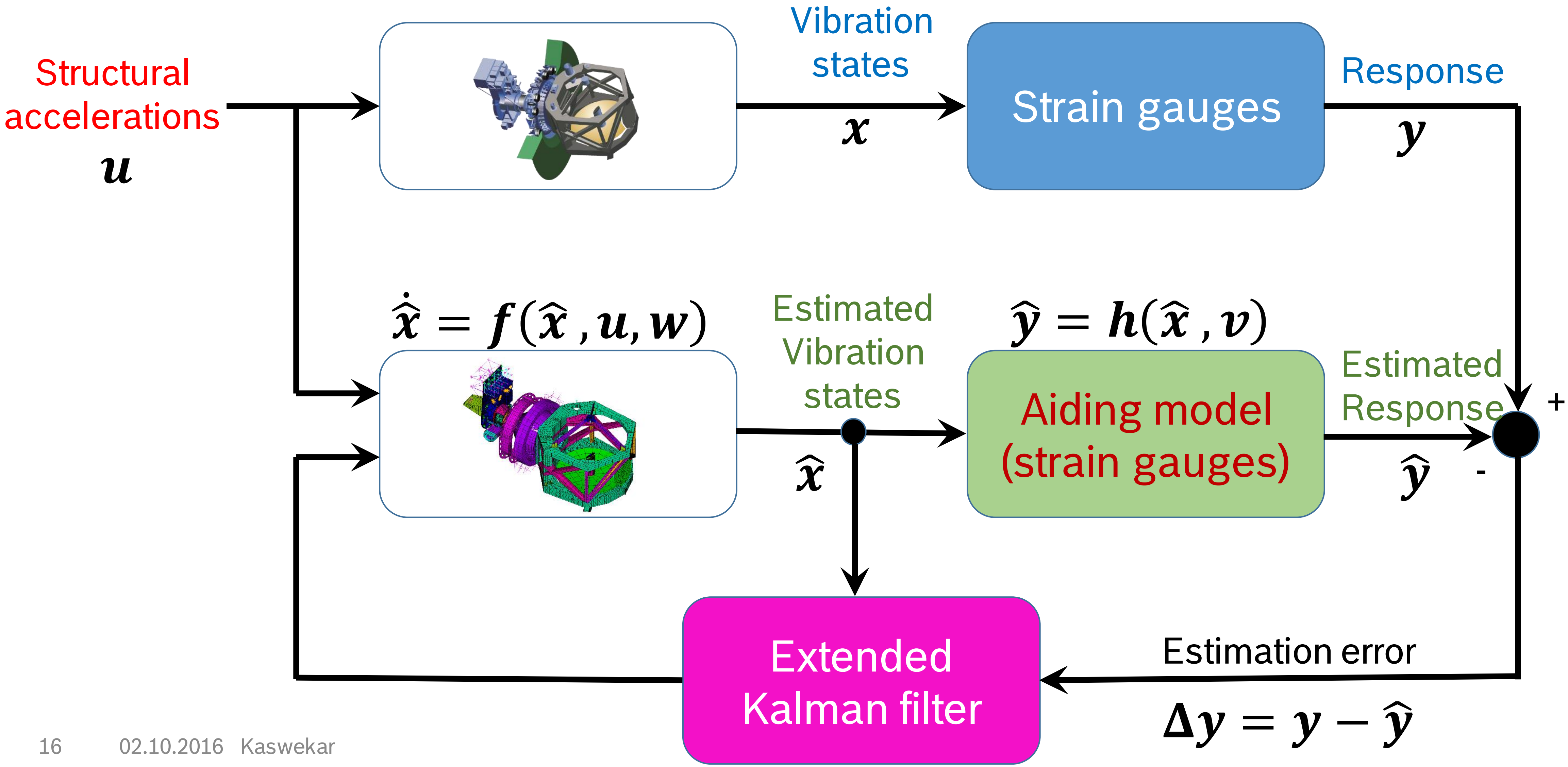
True Image Motion





- <u>Higher amplitude peaks</u> : due to harmonic excitation at fine drive
- <u>Low amplitude peaks</u>: natural frequencies excited due to initial condition

State (modal) observer for the telescope structure



Structural accelerations

$\boldsymbol{u}$

Vibration states

$\boldsymbol{x}$

Strain gauges

Response

$\boldsymbol{y}$

$$\dot{\hat{\boldsymbol{x}}} = \boldsymbol{f}(\hat{\boldsymbol{x}}, \boldsymbol{u}, \boldsymbol{w})$$

Estimated Vibration states

$\hat{\boldsymbol{x}}$

$$\hat{\boldsymbol{y}} = \boldsymbol{h}(\hat{\boldsymbol{x}}, \boldsymbol{v})$$

Aiding model (strain gauges)

Estimated Response

$\hat{\boldsymbol{y}}$

+

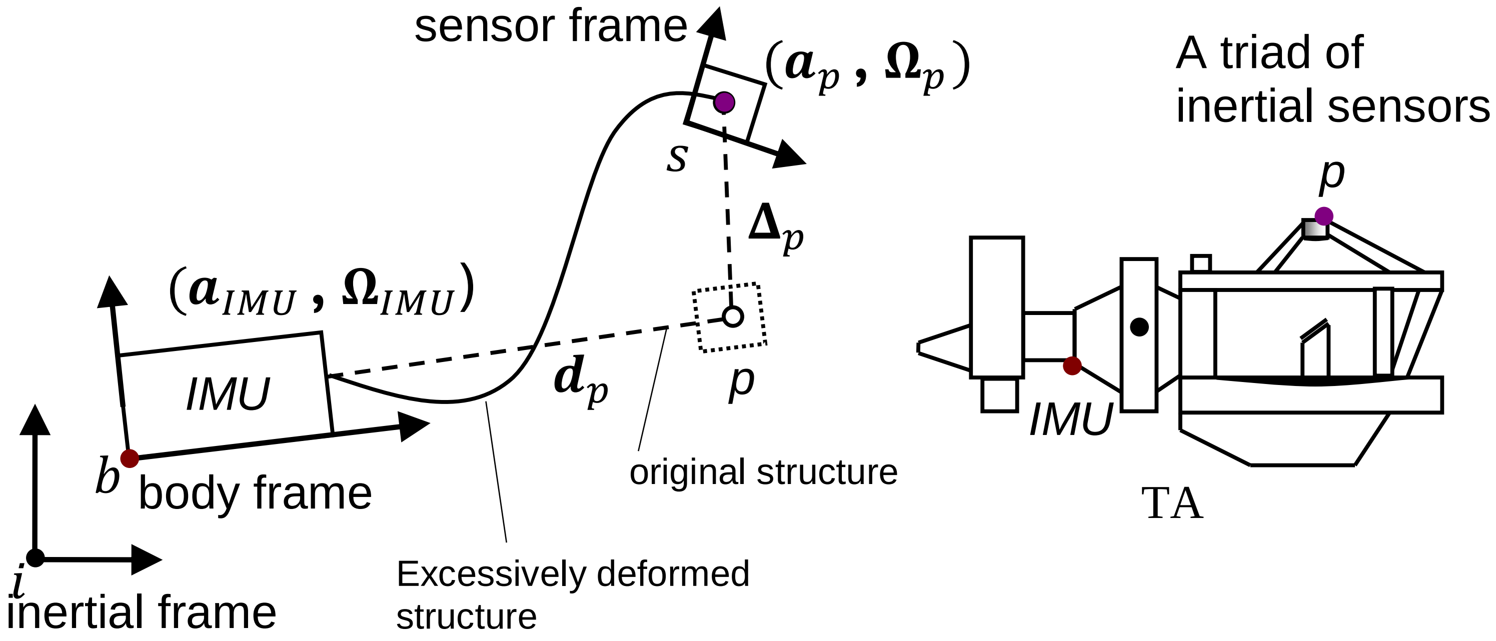
-

Extended Kalman filter

Estimation error

$$\boldsymbol{\Delta y} = \boldsymbol{y} - \hat{\boldsymbol{y}}$$

Relative motion kinematics



$$\boldsymbol{\Delta}_p = \sum_{j=1}^{5} \hat{q}_j \, \xi_j(t)$$

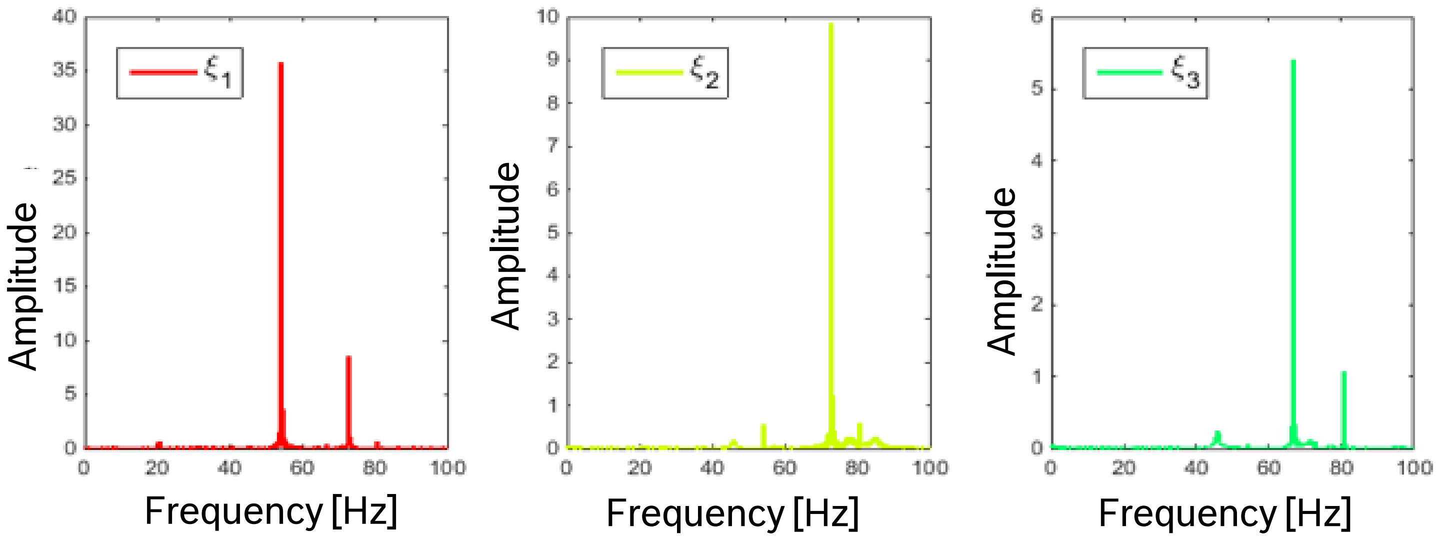
(Five target modes)

$$\ddot{\xi}_j(t) = \sum_{p=1}^{20} \tilde{f}_p\left({}^{s}_{i}\boldsymbol{a}_p,\ {}^{b}_{i}\boldsymbol{a}_{IMU},\ {}^{b}_{i}\boldsymbol{\Omega}_{IMU},\ {}^{b}_{i}\dot{\boldsymbol{\Omega}}_{IMU}, \boldsymbol{d}_p,\ {}^{b}\widehat{\boldsymbol{Q}},\ {}^{b}\boldsymbol{T}_s\,, \dot{\xi}_j\,, \xi_j\right)$$

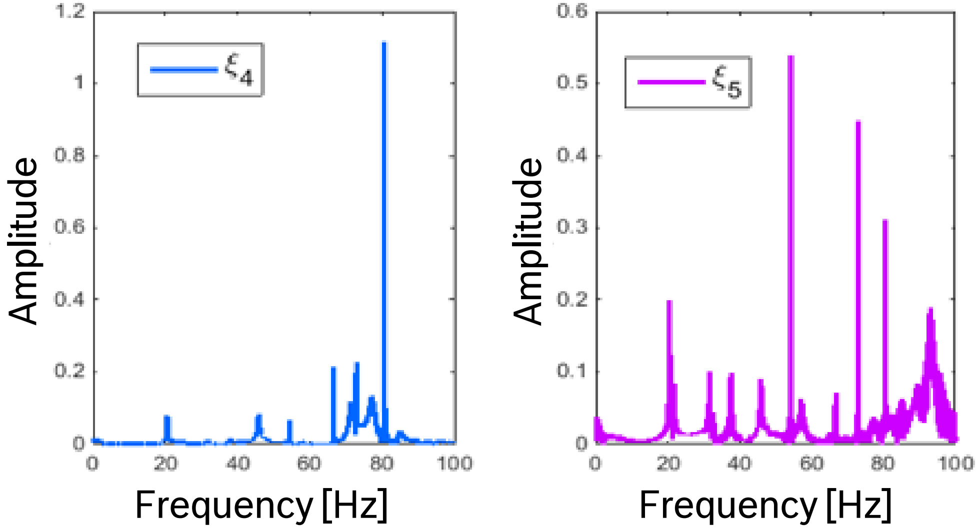
(Twenty accelerometers)

Estimated modal coordinates, Fourier Analysis

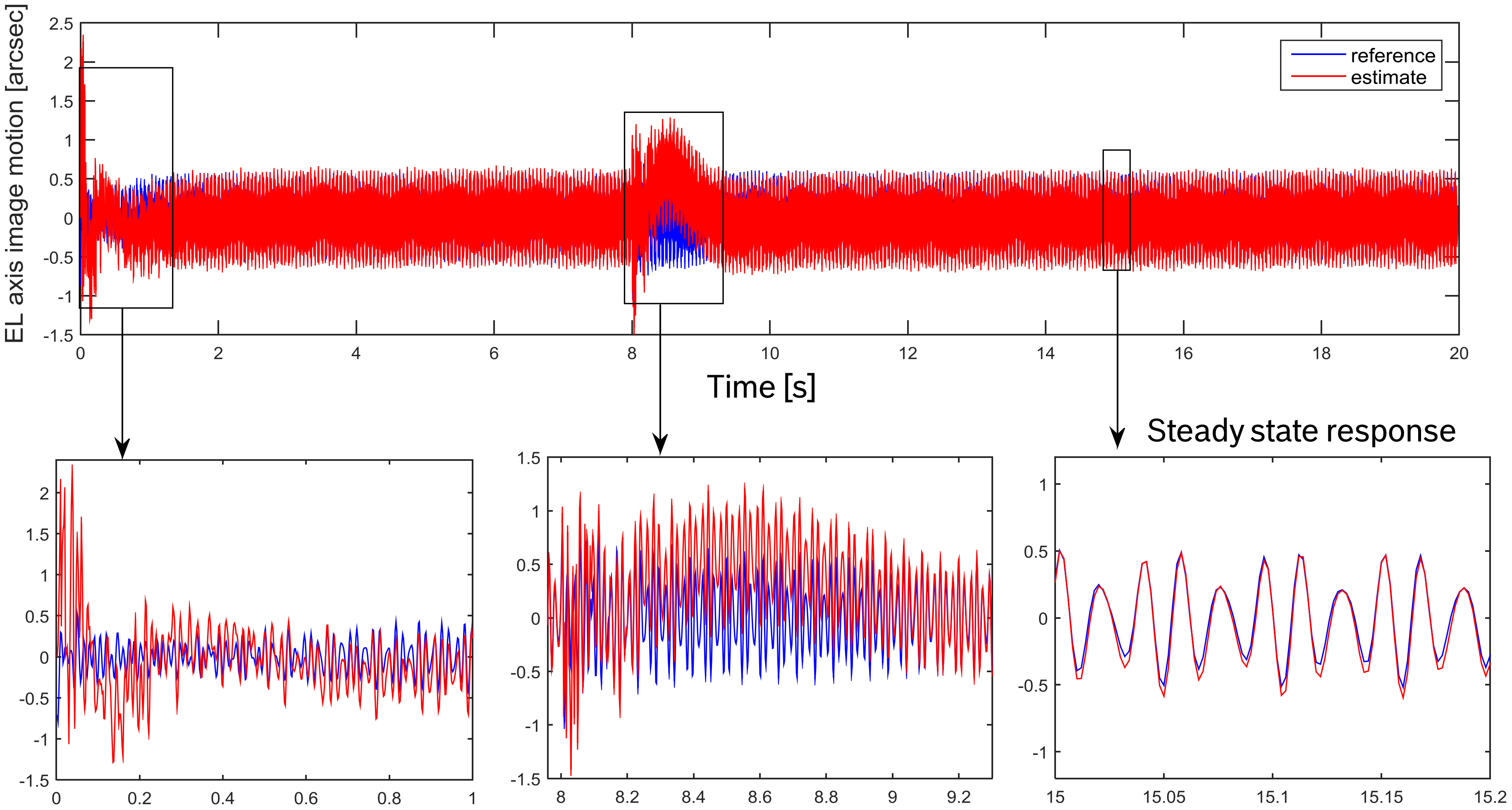
Targeted modes [Hz]
54.27
72.80
66.63
80.68
93.17



- The frequency response is distributed among the *modal coefficients*
- *Aliasing* of non-targeted modes can be seen
- Weak coupling of the targeted modes

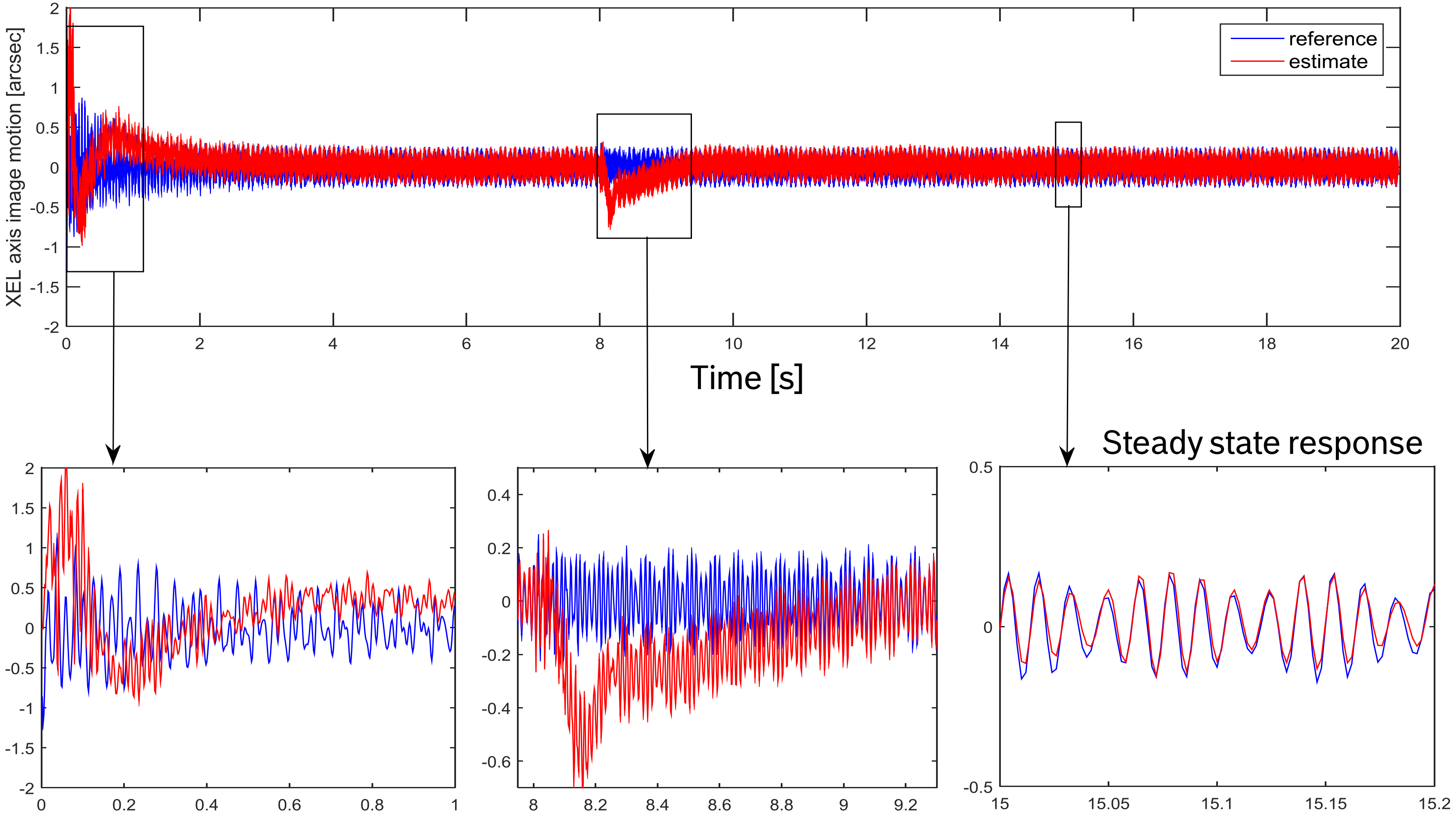


Elevation axis image motion, time response



- The observer converges quickly and gives good estimate in the steady state region
- The sudden impulse at t = 8 s (unusual for real telescope)

Cross Elevation axis image motion, time response

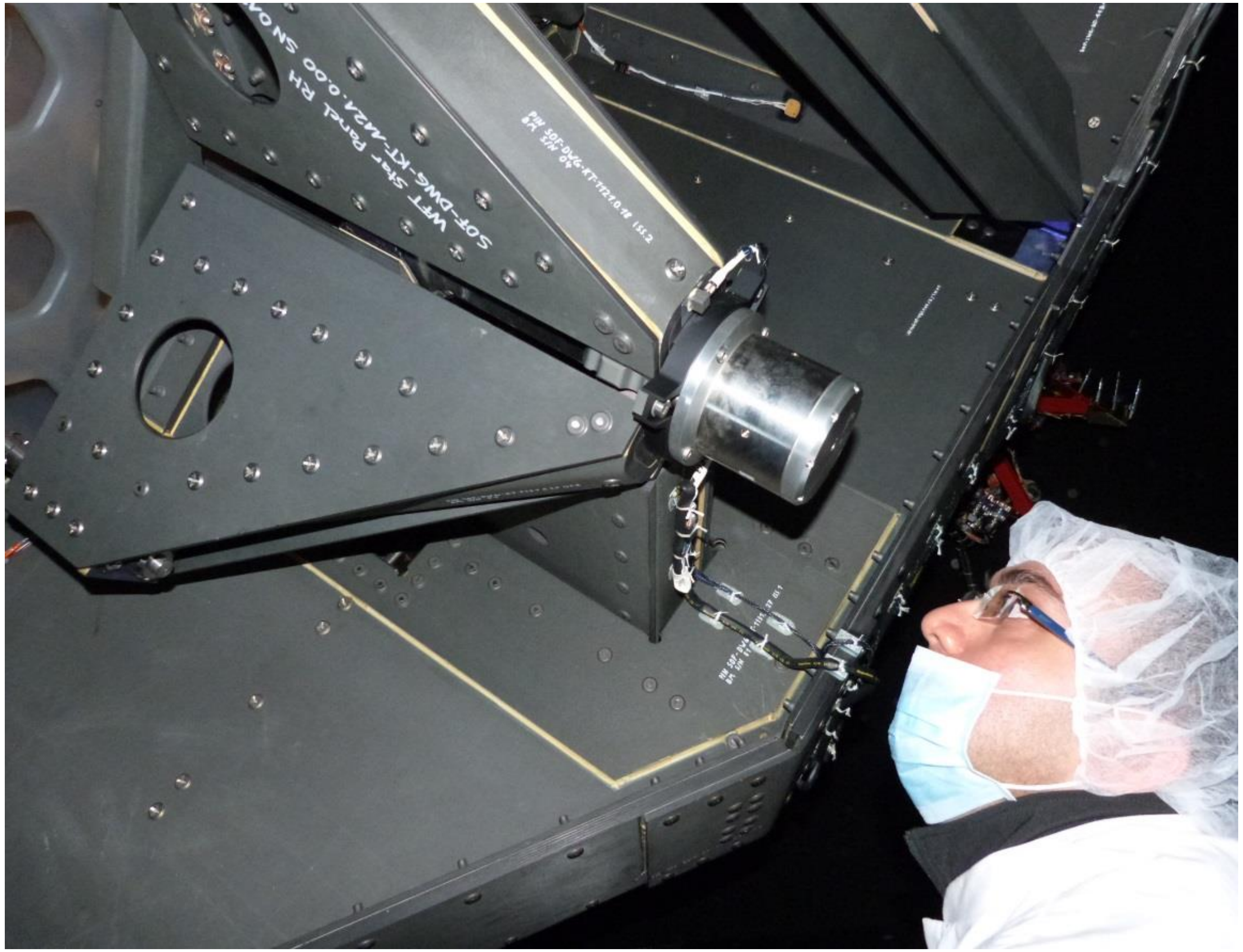


- The observer converges quickly and gives good estimate in the steady state region
- The sudden impulse at t = 8 s (unusual for real telescope)

Summary

- The multi sensor data fusion can be used effectively to estimate modal coordinates of three-dimentional lightweight structure
- Optimal sensor placement and the number of inertial sensors play a key role
- More number of sensors → reduction in the aliasing effect
- A priori estimate of mode shapes of the structure is required

Sensor Fusion Based Integrated Motion Measurement for Telescope Structures



Kaswekar, P.; Wagner, J. F. : Sensor fusion based vibration estimation using inertial sensors for a complex lightweight structure. In: Inertial Sensors and Systems, Symposium Gyro Technology, Karlsruhe, Germany, 2015