Metrology and Control of Large Telescopes workshop, 2016, Green Bank , US

Wind Effect and its Compensation for Large Reflector Antennas

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Outline

Motivation

Wind Effect Analysis

Control Compensation

Mechatronics Design

Conclusions

Outline

- **Motivation**
- **Wind Effect Analysis**
- **Control Compensation**
- **Mechatronics Design**
- **Conclusions**

Motivation

Large reflector antenna

Advantages

- Narrow beam
- High gain

Applications

- Radio astronomy
- Satellite communication
- Deep space exploration

…

Motivation

Higher gain

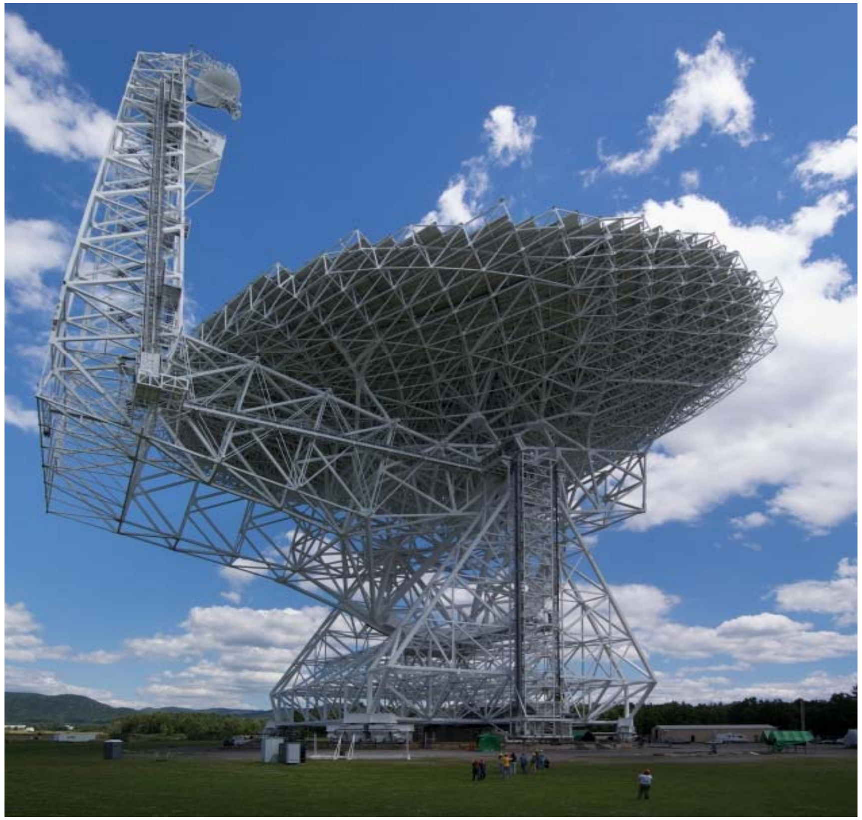
Better resolution

Larger reflector

Higher working frequency

Higher pointing accuracy

Green Bank Telescope,2008
D:100×110m/100MHz-115GHz



Pointing Accuracy Requirement:
4 arcseconds

Motivation

Higher gain

Better resolution

↓

Larger reflector

Higher working frequency

↓

Higher pointing accuracy

Larger windward area → Disturbance ↑

More flexible → Oscillation ↑

More sensitive to deformation

↓

Pointing accuracy ↓

The required pointing accuracy could be satisfied only when there is no wind !

Motivation

Higher gain

Better resolution

Larger reflector

Higher working frequency

Higher pointing accuracy

Radome

Angular displacement

Decrease its gain

High cost, size limitation

Most Large Reflector Antennas work in open air

Motivation

Higher gain

Better resolution

↓

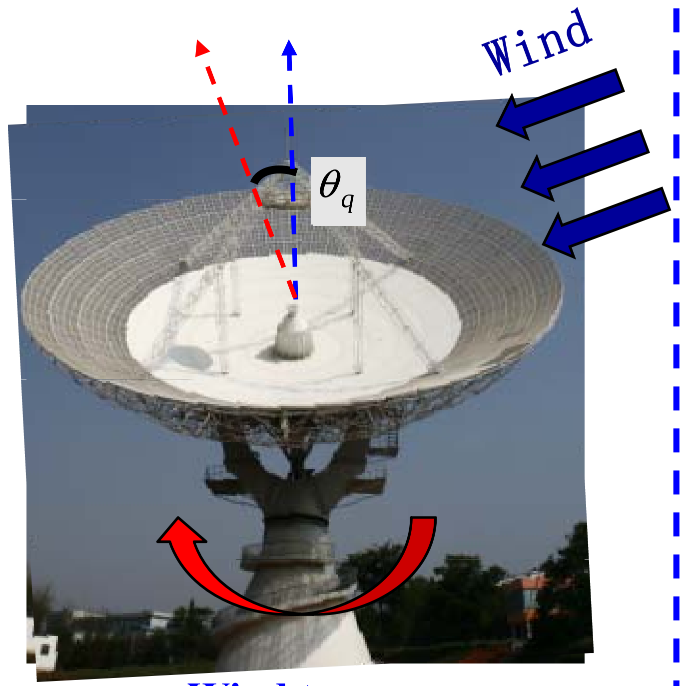
Larger reflector

Higher working frequency

⇩

Higher pointing accuracy

Compensation →



Wind torque

↑

Excess drive torque

Gawronski W.. Antenna control systems: from PI to H infinity, IEEE Antennas and Propagation Magazine, 2001, 43(1): 52-60.

Gawronski W., Ahlstrom, Jr.. Analysis and performance of the control system of the NASA 70-meter antennas. ISA transactions, 2004, 43: 597-610.

Motivation

Higher gain

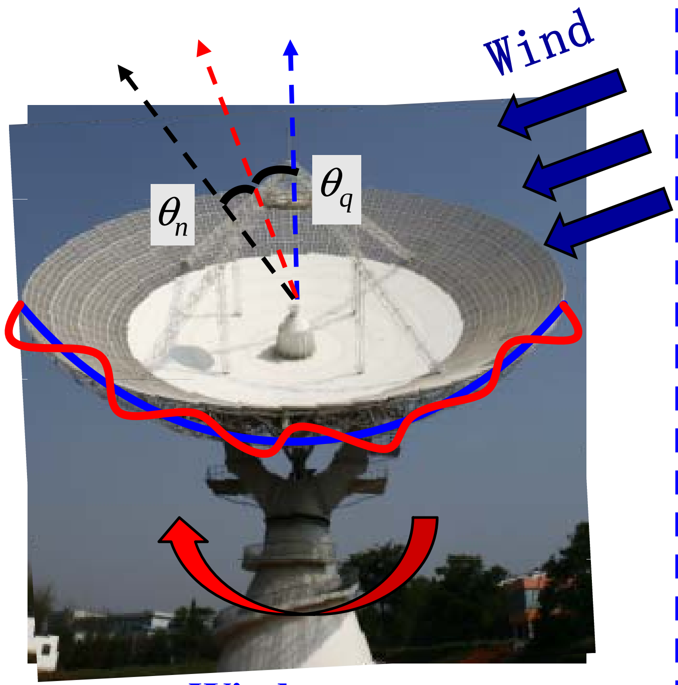
Better resolution

Larger reflector

Higher working frequency

Higher pointing accuracy

Compensation



Wind torque

Wind pressure

Motivation

Higher gain

Better resolution

Larger reflector

Higher working frequency

Higher pointing accuracy

Compensation

66m S/X band antenna

Operation condition： wind speed of 10m/s

Rotation angle error： 29.52arcsec(RMS)

Flexible pointing error： 21.96arcsec(RMS)

Total pointing error： 32.76arcsec(RMS)

Motivation

Higher gain

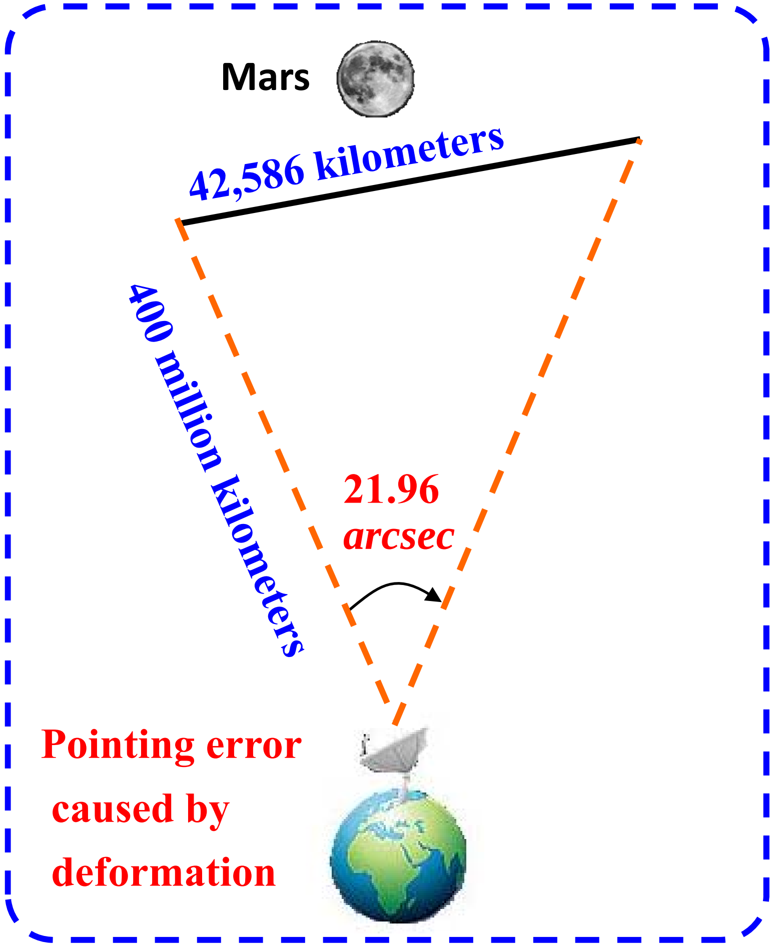
Better resolution

Larger reflector

Higher working frequency

Higher pointing accuracy

Compensation



Motivation

Higher gain

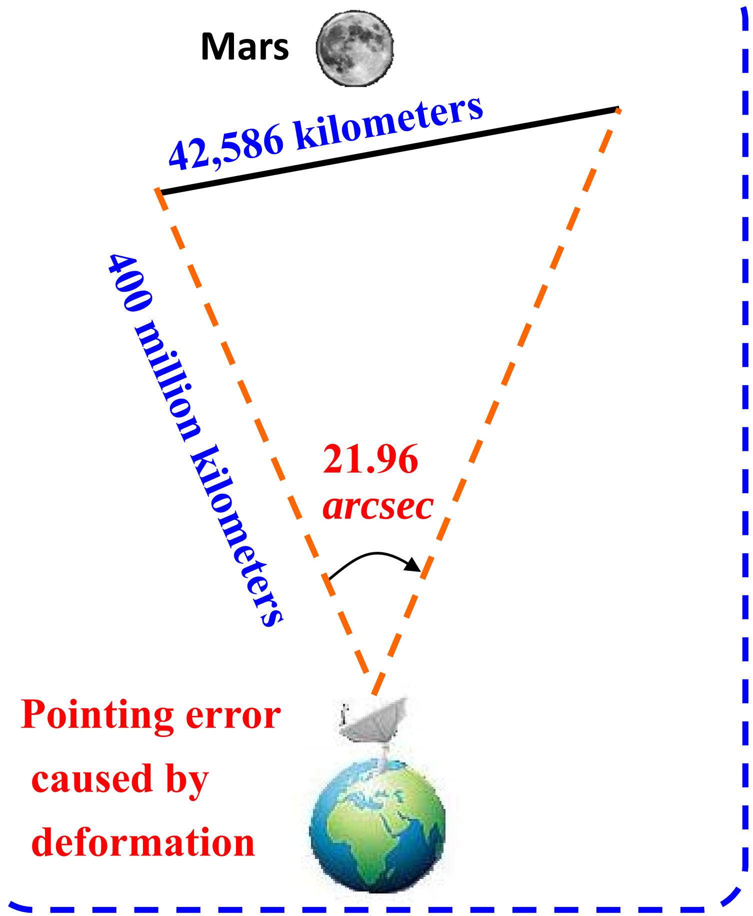
Better resolution

Larger reflector

Higher working frequency

Higher pointing accuracy

Compensation



Analysis **Compensation**

Open Problem

Outline

- Motivation
- **Wind Effect Analysis**
- Control Compensation
- Mechatronics Design
- Conclusions

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Wind Effect Analysis

Antenna Structure Model

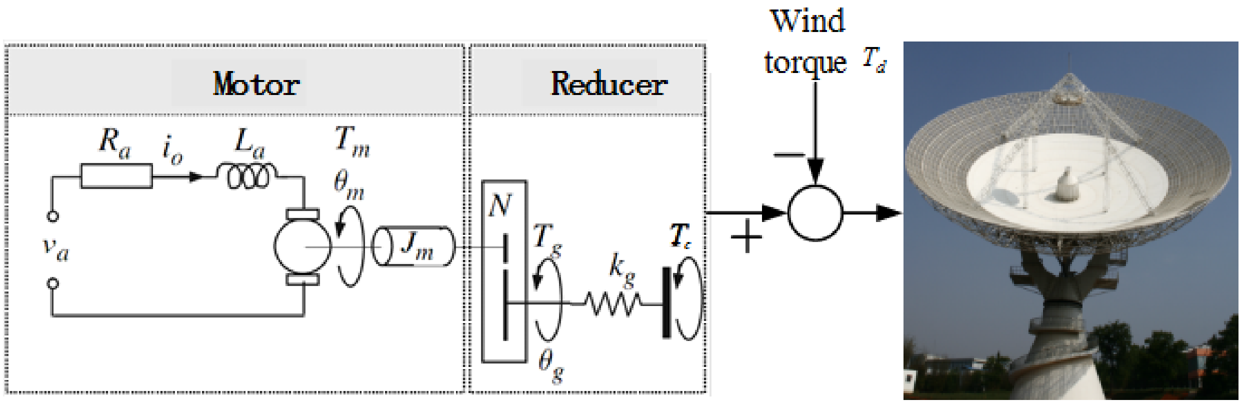
Traditional

PCOM

Rigid model

Advantage: Lower order

Disadvantage: Without any flexible information



※That’s why the pointing error caused by flexible deformation could not be compensated with those proposed methods.

Wind Effect Analysis

Antenna Structure Model

- Traditional
- PCOM

Rigid model

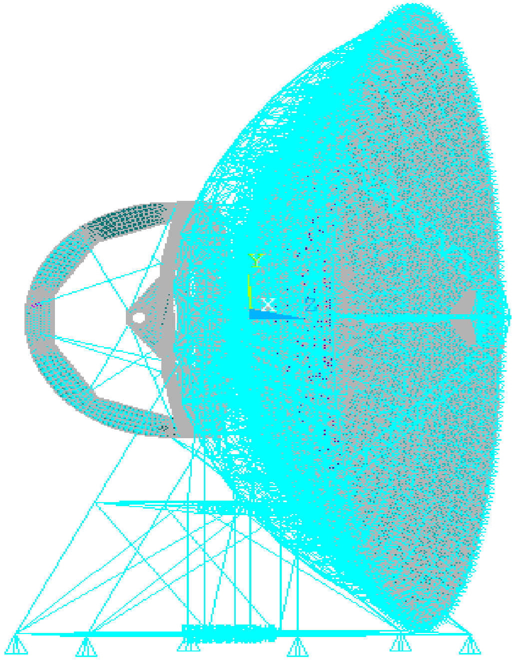
Advantage: Lower order

Disadvantage: Without any flexible information

Finite element model

Advantage: Describing flexible oscillation

Disadvantage: Too much degree of freedom



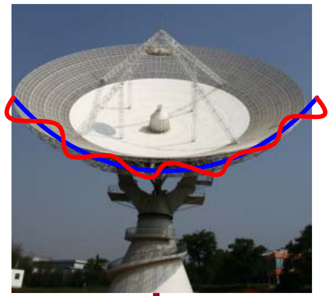
Wind Effect Analysis

Antenna Structure Model

Traditional

PCOM

Pointing Control – Oriented Model



Rigid model: $T = J\ddot{\theta} + D_r\dot{\theta}$

Flexible model: $M\ddot{q} + D\dot{q} + Kq = B_0 u$

$y = C_{oq}q + C_{ov}\dot{q}.$

$q = \Phi q_m.$

$$\begin{bmatrix} J & 0 \\ B_{11}\cdot J & \boxed{M_m} \end{bmatrix}\begin{bmatrix} \ddot{\theta} \\ \ddot{q}_m \end{bmatrix} + \begin{bmatrix} D_r & 0 \\ B_{11}\cdot D_r & \boxed{D_m} \end{bmatrix}\begin{bmatrix} \dot{\theta} \\ \dot{q}_m \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \boxed{K_m} \end{bmatrix}\begin{bmatrix} \boxed{\theta} \\ q_m \end{bmatrix} = \begin{bmatrix} T_1 & 0 \\ 0 & F \end{bmatrix}\begin{bmatrix} 1 \\ B_{12} \end{bmatrix}$$

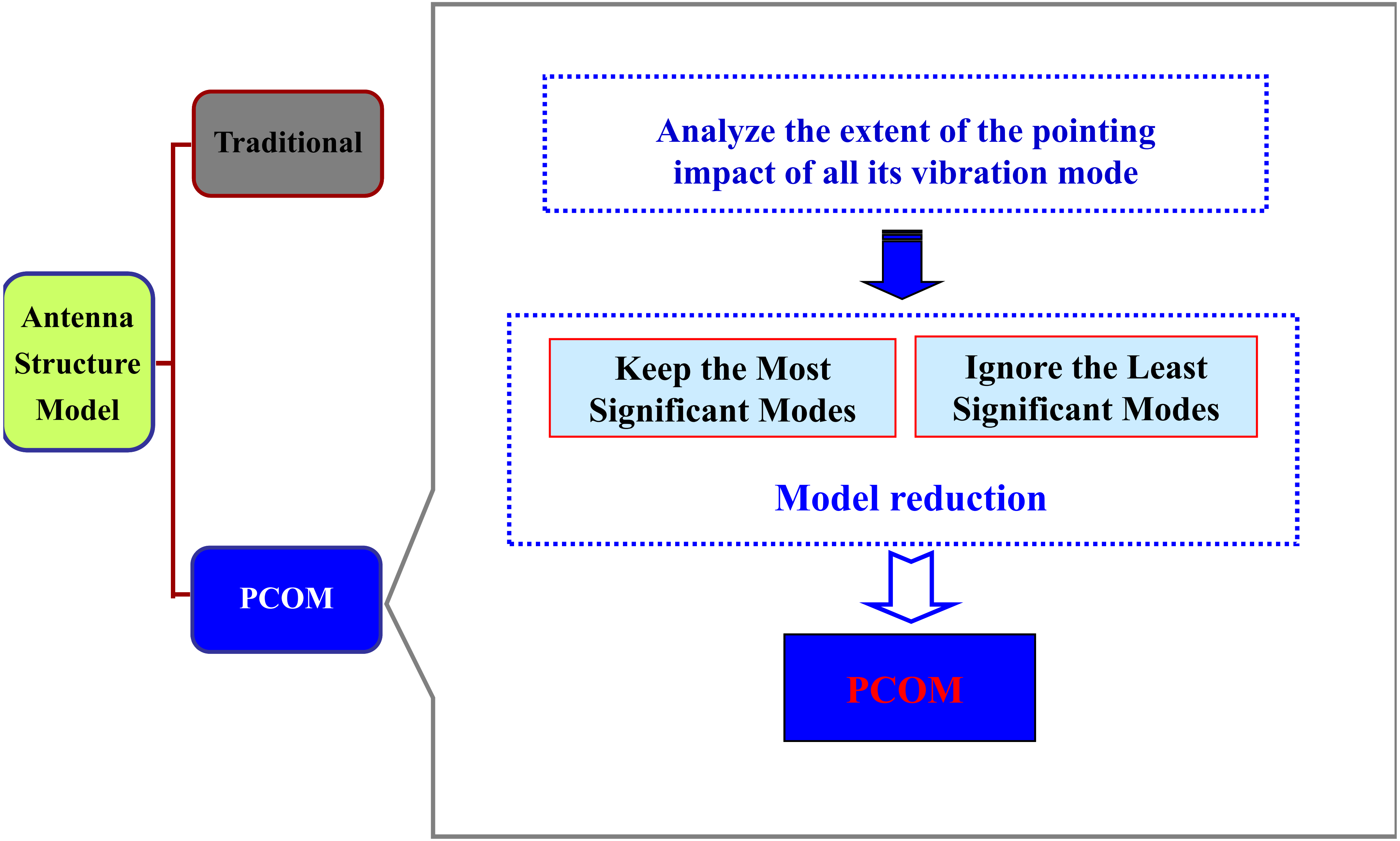
Rotation Angle

Nodes displacements

$$\boxed{y} = C_{mq}q_m$$

Nodes displacements could evaluate the deformation of the structure

Wind Effect Analysis

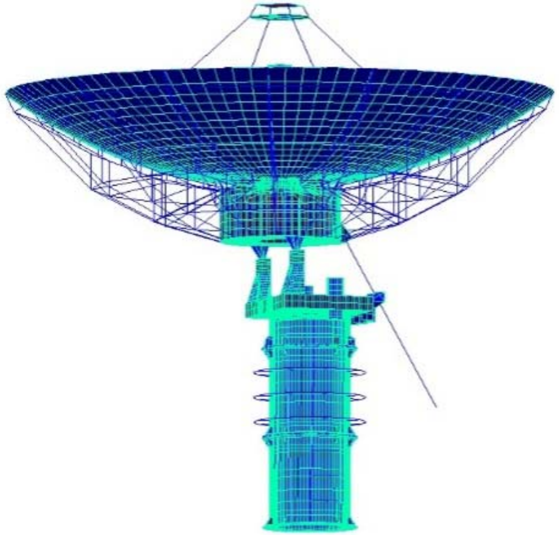


Wind Effect Analysis

FE Modeling | Model Calibration | PCOM construction

Antenna Structure Model

- Traditional
- PCOM



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Wind Effect Analysis

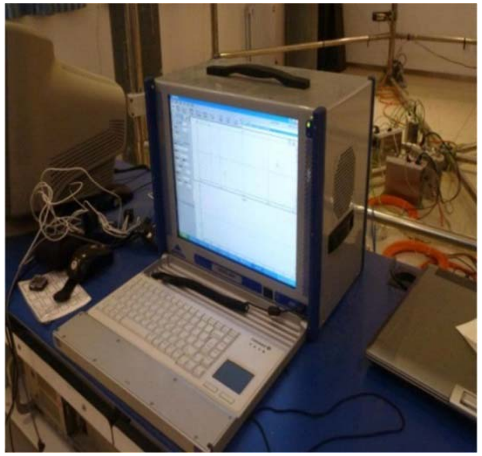
Antenna Structure Model

Traditional

PCOM

FE Modeling | **Model Calibration** | PCOM construction

Model test



Load deformation test

Wind Effect Analysis

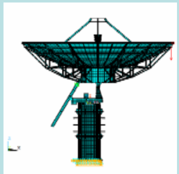
Antenna Structure Model

Traditional

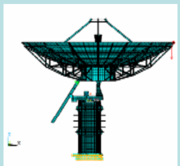
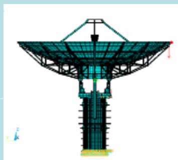
PCOM

FE Modeling | **Model Calibration** | PCOM construction

Natural Frequency

Test content	Load （Kg）	Test results （Hz）	Simulation results （Hz）	Relative error
	50	6.84	7.30	6.72%
	100	6.84		

Deformation

Test content	Load (Kg)	Test results (mm)	Calculate results (mm)	Relative error
	50	-0.677	-0.743	9.74%
	100	-1.679	-1.566	6.73%
	50	-0.506	-0.532	5.13%
	100	-1.236	-1.163	5.91%

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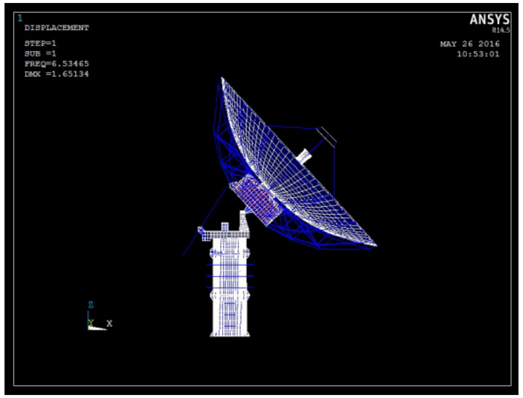
Wind Effect Analysis

Antenna Structure Model

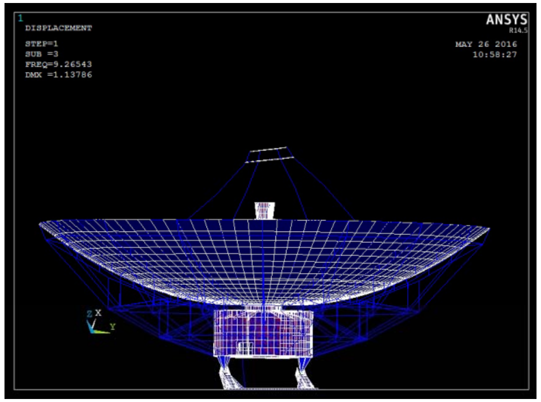
- **Traditional**
- **PCOM**

FE Modeling	Model Calibration	**PCOM construction**

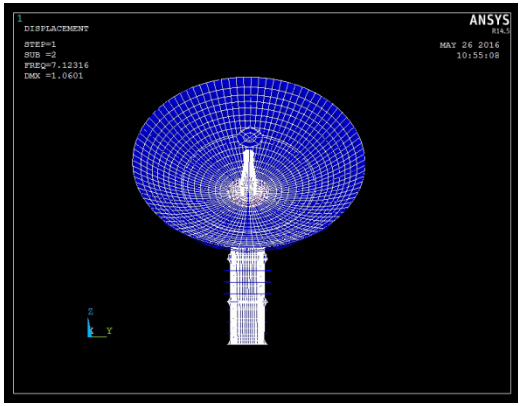
Main reflector Deformation	Feed displacement	Sub-reflector displacement	Sub-reflector rotation



The 1st order



The 3rd order



The 2nd order

Order	Energy ratio	Pointing error in AZ(°)
1	0.248	7.08×10^{-4}
2	0.395	3.56×10^{-3}
3	0.008	4.90×10^{-4}
	0.08%	**9.4%**

Wind Effect Analysis

Antenna Structure Model

- Traditional
- PCOM

FE Modeling | Model Calibration | **PCOM construction**

$$\theta_p = \boxed{\theta} + \boxed{\theta_n} = \theta + \boxed{F} \sum_{i=1}^{\boxed{k}} \boxed{G_i}$$

Shaft rotation angle

Pointing error caused by deformation

Wind force

The order kept

pointing error caused by each mode

$$G_i = \left(A^{-1}_{5,1}\sum_{s=1}^{n}G_{si}u_s + A^{-1}_{5,2}\sum_{s=1}^{n}G_{si}v_s + A^{-1}_{5,3}\sum_{s=1}^{n}G_{si}w_s + A^{-1}_{5,4}\sum_{s=1}^{n}G_{si}\right)$$
$$-\left|\begin{array}{l}\left(A^{-1}_{5,1}\sum_{s=1}^{n}G_{si}u_s + A^{-1}_{5,2}\sum_{s=1}^{n}G_{si}v_s + A^{-1}_{5,3}\sum_{s=1}^{n}G_{si}w_s + A^{-1}_{5,4}\sum_{s=1}^{n}G_{si}\right)(L_1+L_3) \\ +L_2\left(A^{-1}_{5,1}\sum_{s=1}^{n}G_{si}u_s + A^{-1}_{5,2}\sum_{s=1}^{n}G_{si}v_s + A^{-1}_{5,3}\sum_{s=1}^{n}G_{si}w_s + A^{-1}_{5,4}\sum_{s=1}^{n}G_{si}\right) \\ -\left(A^{-1}_{1,1}\sum_{s=1}^{n}G_{si}u_s + A^{-1}_{1,2}\sum_{s=1}^{n}G_{si}v_s + A^{-1}_{1,3}\sum_{s=1}^{n}G_{si}w_s + A^{-1}_{1,4}\sum_{s=1}^{n}G_{si}\right) \\ -(G_{iB} + |G_{iB} + G_{iN} + L_1 G_{i\theta}| / M + L_3 G_{i\theta})\end{array}\right| K_w / f$$

Pointing error caused by main reflector

Pointing error caused by feed

Pointing error caused by sub-reflector

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Wind Effect Analysis

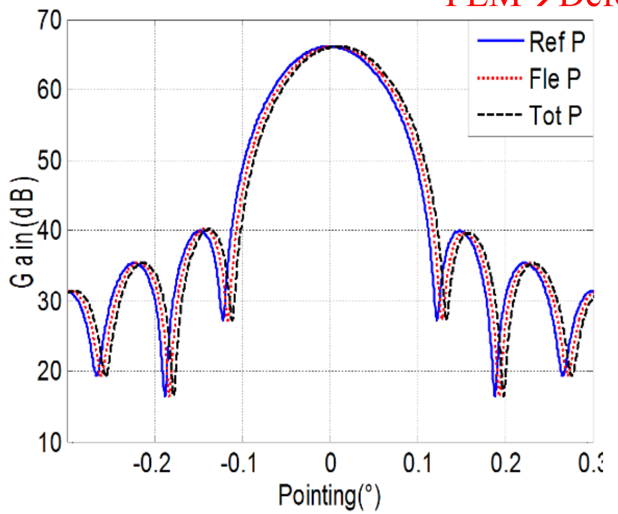
Antenna Structure Model

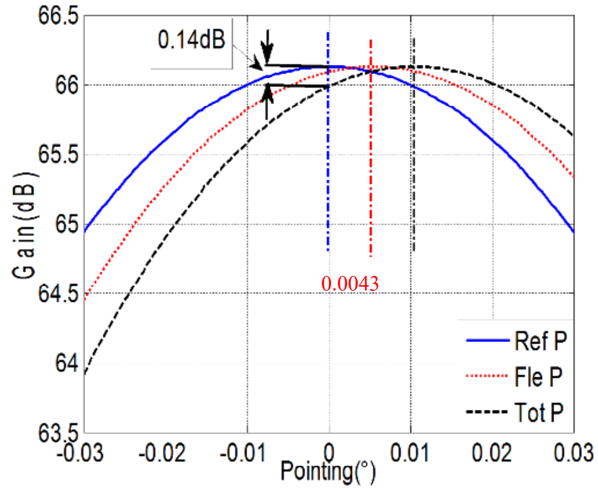
- Traditional
- PCOM

FE Modeling | Model Calibration | **PCOM construction**

MAX DEFORMATIONS UNDER A 10M/S WIND SPEED	
Main reflector rotation (deg)	2.66×10^{-3}
Displacement of the vertex (m)	0.88×10^{-5}
Displacement of the feed (m)	-0.55×10^{-5}
Displacement of the sub-reflector(m)	0.50×10^{-4}
Sub-reflector rotation (deg)	-4.48×10^{-4}

FEM→Deformed Refector →GRASP





	PCOM	GRASP	Relative error
Pointing error	0.0041°	0.0043°	4.6%

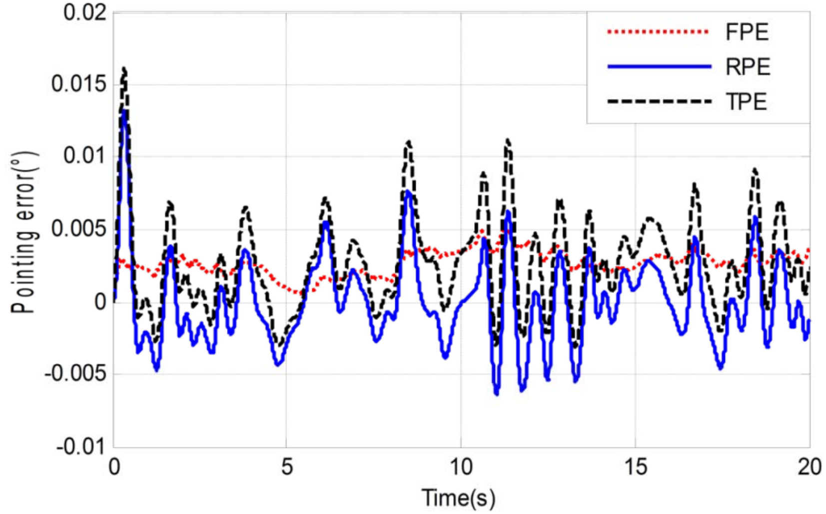
Wind Effect Analysis

Antenna Structure Model

Traditional

PCOM

FE Modeling	Model Calibration	**PCOM construction**



	Max error(deg)	RMS error(deg)
FPE	0.0053	0.0028
RPE	0.0077	0.0030
TPE	0.0112	0.0042

FPE: Flexible pointing error

RPE: Rotation error

TPE: Total pointing error

Wind torque and force almost have the same impact on pointing error

Jie Zhang, Jin Huang*, Lili Qiu, et al, Analysis of reflector vibration-induced pointing errors for large antennae subject to wind disturbance, *IEEE Antennas and Propagation Magazine*, 2015, 57(6): 46-61.

Outline

Motivation

Wind Effect Analysis

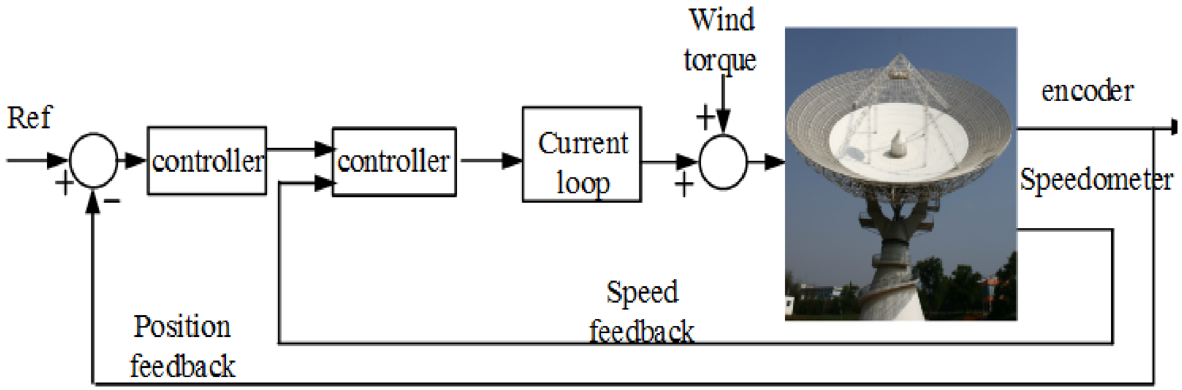
Control Compensation

Mechatronics Design

Conclusions

Passive Compensation

Traditional control method and improved PID:



Traditional pointing servo control

Disadvantage:
flexible formation induced pointing error was neglected.

Estimating
Disturbance or Over all pointing error

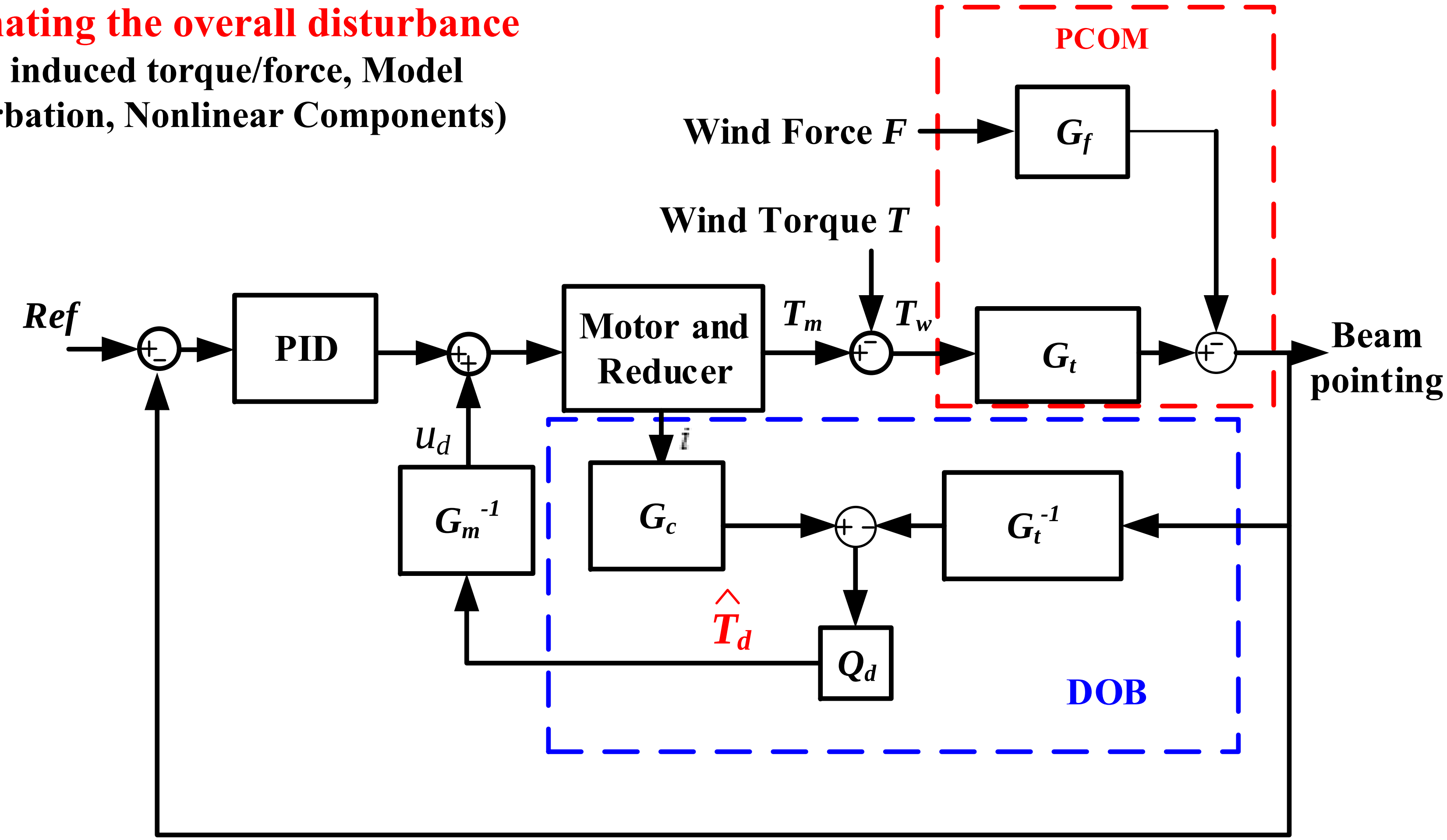
- **Disturbance Observer** → **Feedforward compensation directly**
- **Based on LQG** → **Deriving a optimal control action**
- **Based on predictive control** → **Estimating disturbance and Pointing error for gust**

Passive Compensation

Disturbance Observer（DOB）→

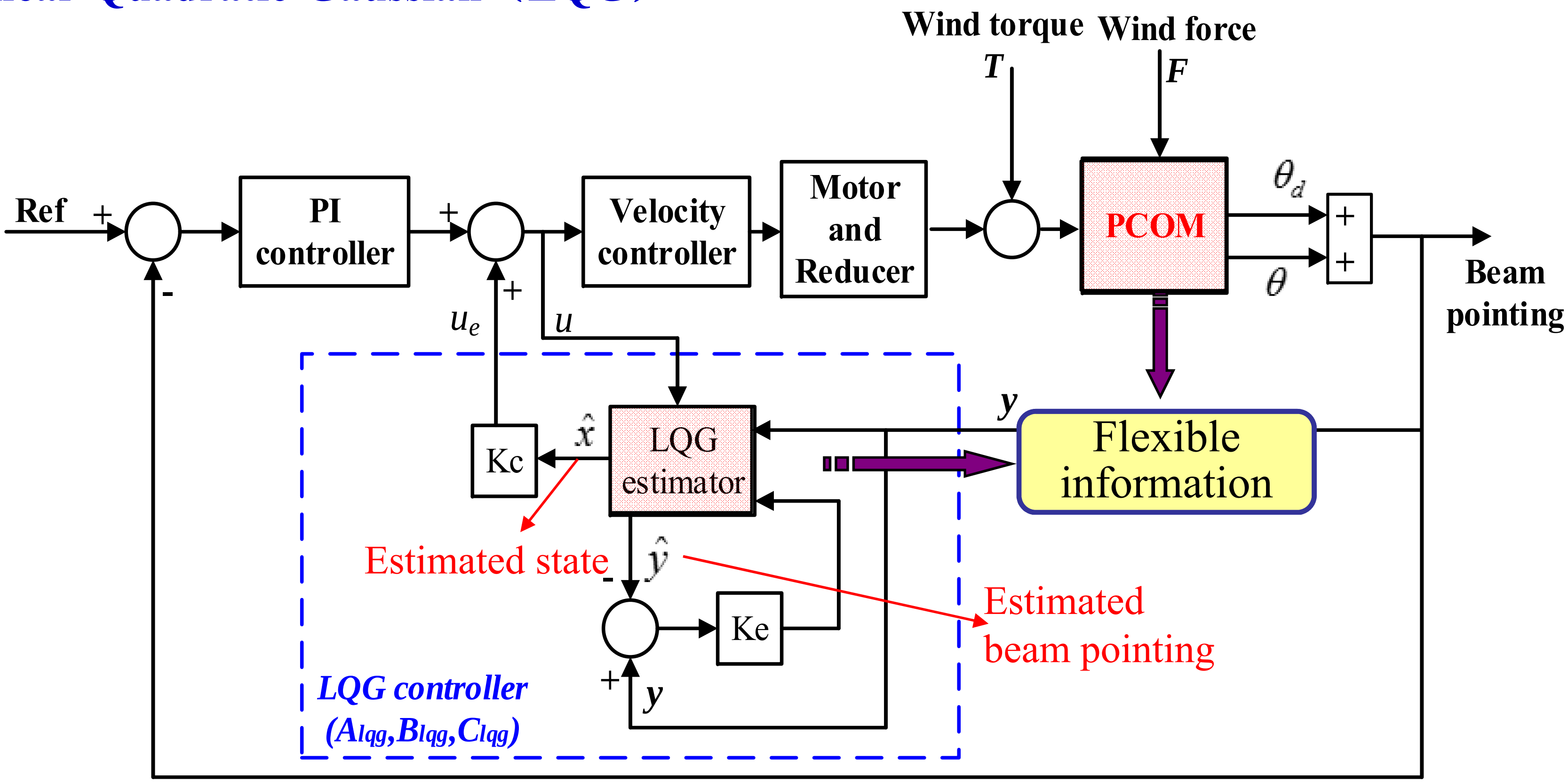
Estimating the overall disturbance

(Wind induced torque/force, Model perturbation, Nonlinear Components)



Passive Compensation

Linear-Quadratic-Gaussian（LQG）



LQG control system based on the PCOM.

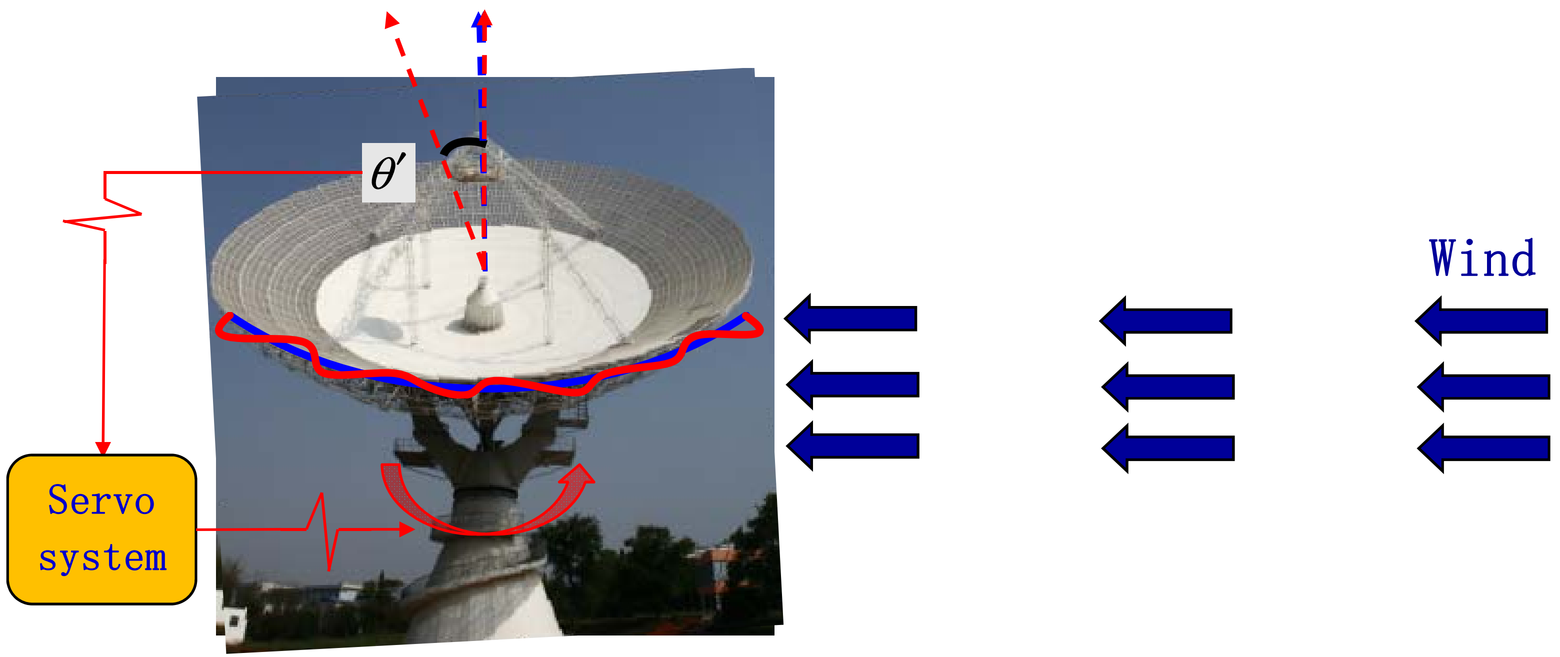
Kc: optimal feedback gain matrix *Kc*: optimal estimator gain matrix

Jie Zhang, Jin Huang* and Jun Zhou et al., A compensator for large antennas based on pointing error estimation under a wind load, *IEEE Trans. Control systems technology*, accepted.

Passive Compensation

Based on DOB	Based on LQG	Based on MPC

Model Predictive Control（ MPC ）→ **Reject the disturbance of gust**



Conventional method

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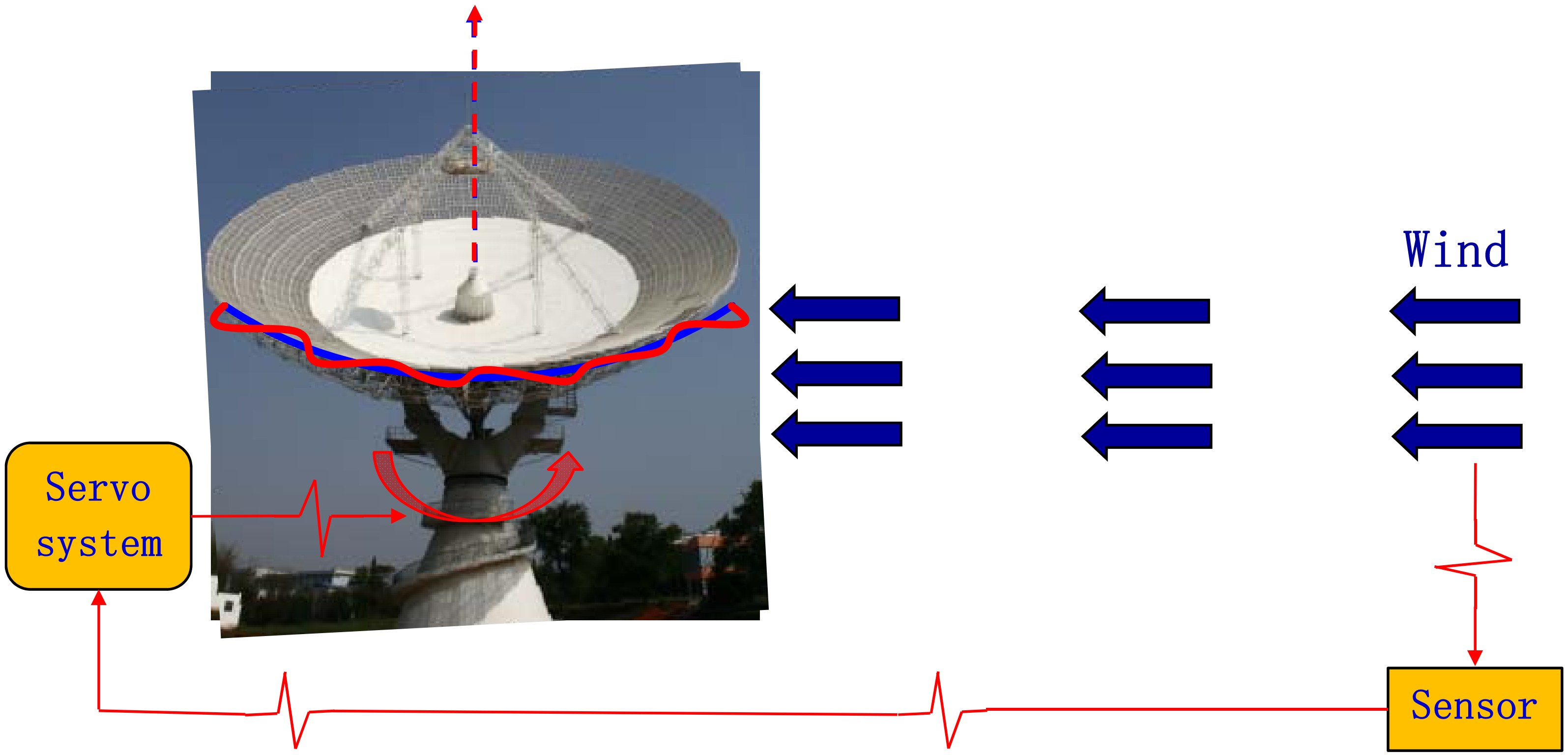
Passive Compensation

Based on DOB	Based on LQG	Based on MPC

Model Predictive Control（ MPC ）→ **Reject the disturbance of gust**

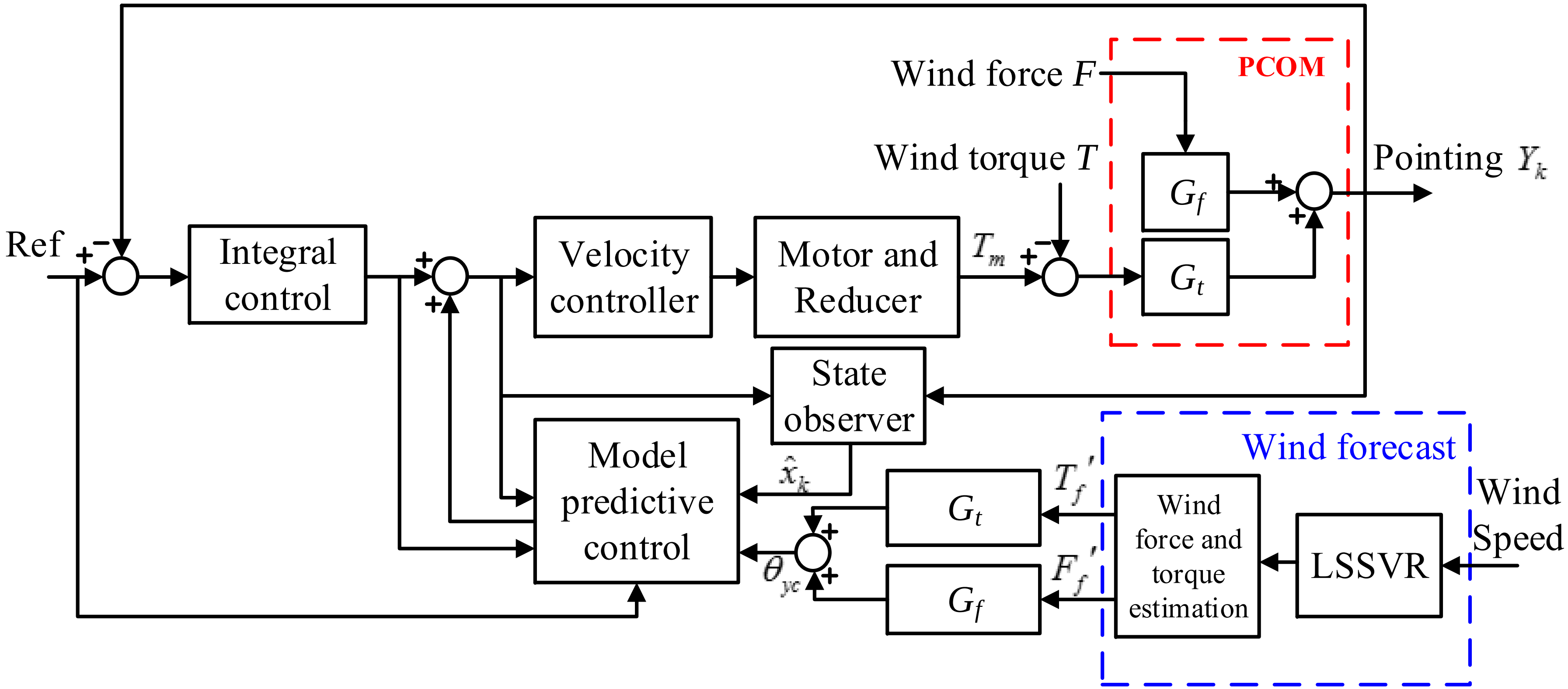


Estimating disturbance with wind field sensing

Passive Compensation

Based on DOB	Based on LQG	Based on MPC

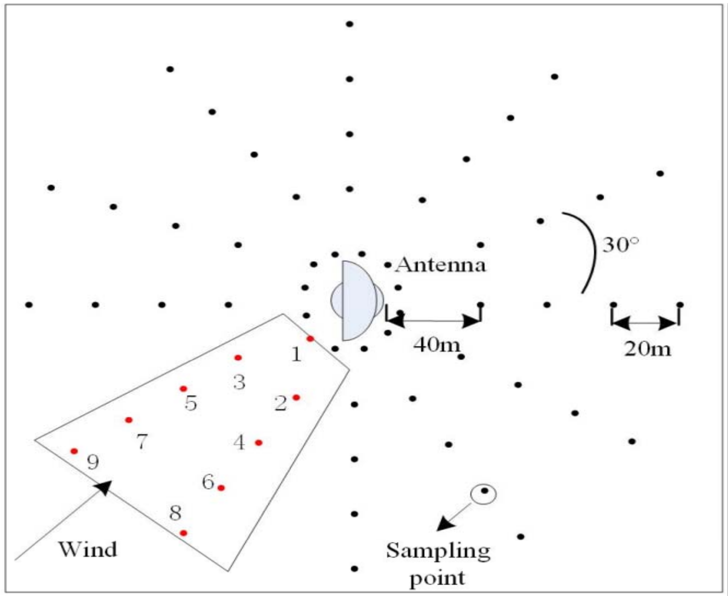
Model Predictive Control（ MPC ）→ **Reject the disturbance of gust**



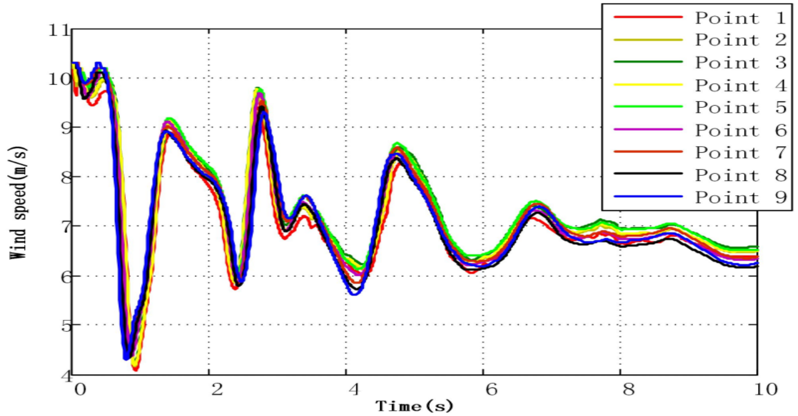
Passive Compensation

Based on DOB	Based on LQG	Based on MPC

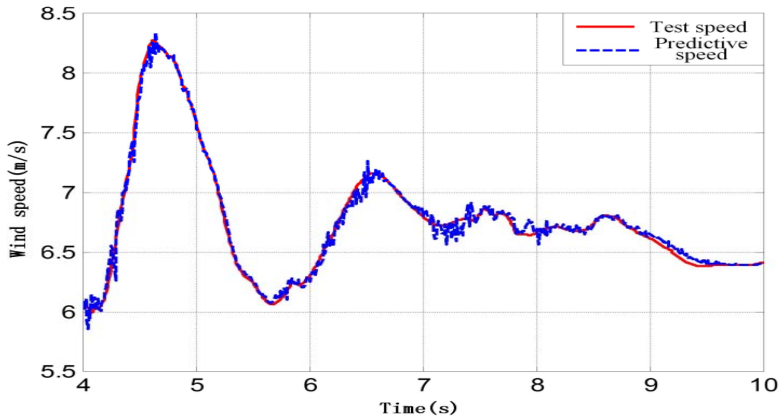
Model Predictive Control（ MPC ）→ Reject the disturbance of gust



Sampling point layout



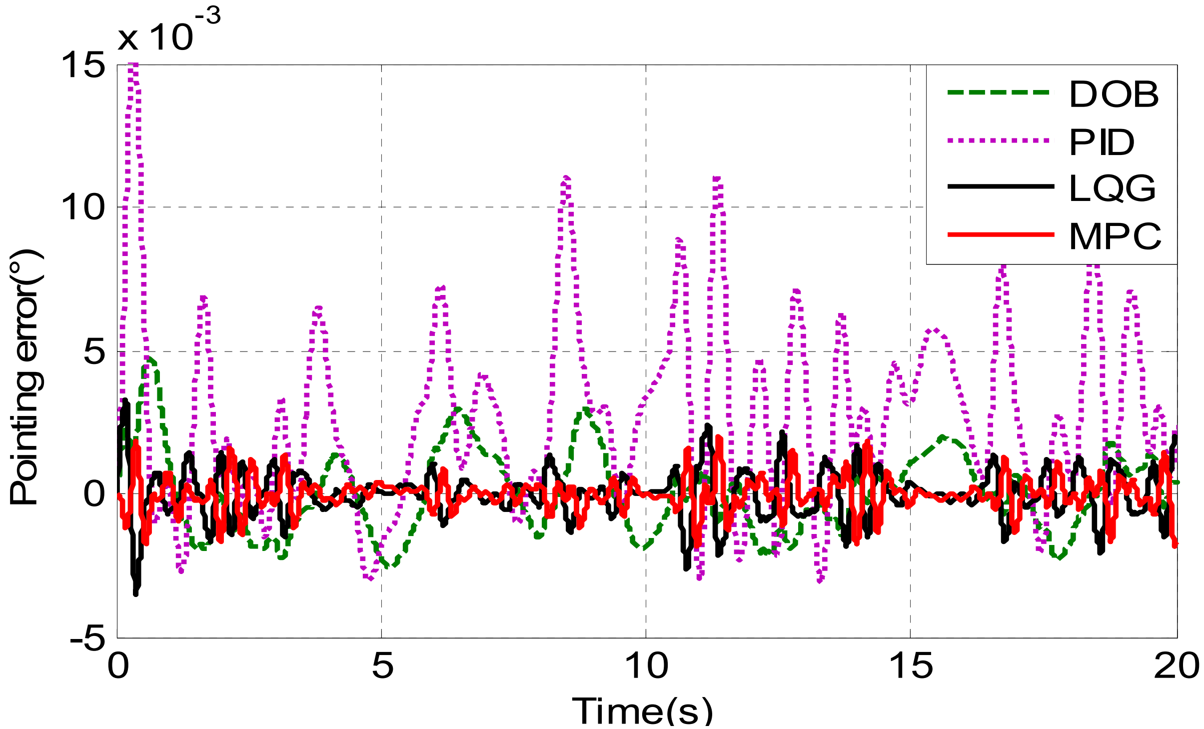
Sampling point wind speed



The comparison between test speed and the prediction speed

Passive Compensation

Simulation results with 7.3m Antenna

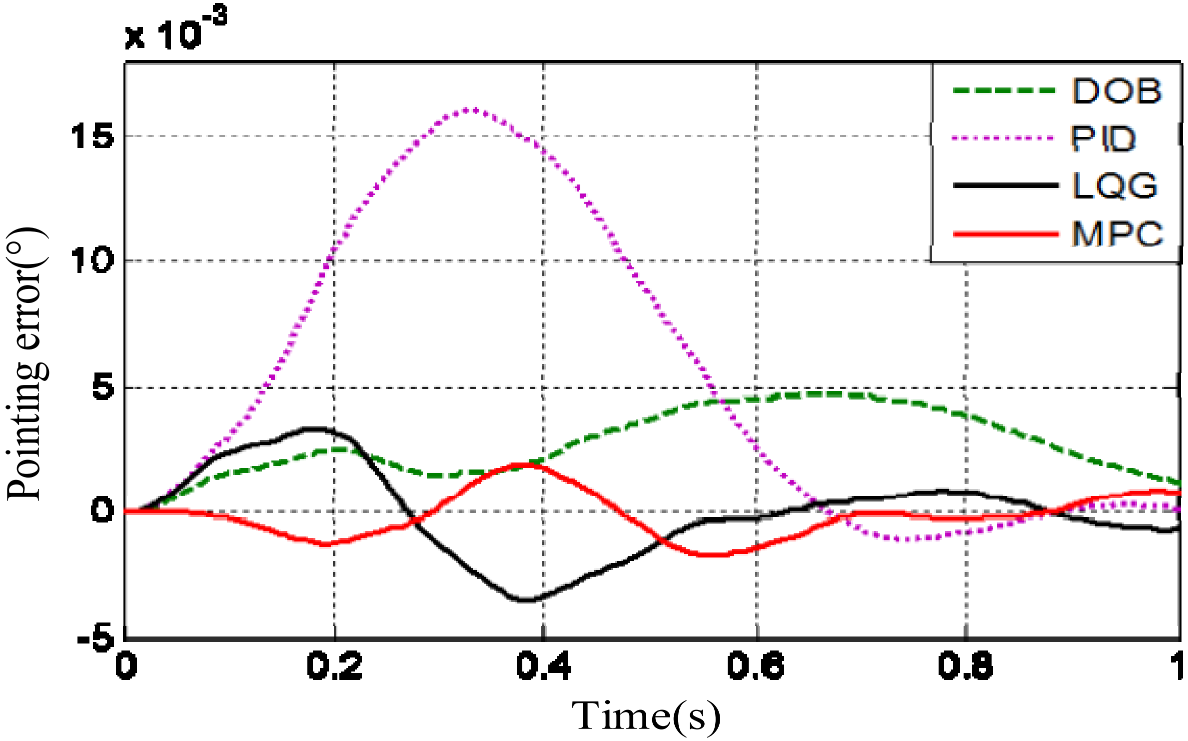


Control method	Max pointing error(°)	RMS pointing error (°)
PID	0.0112	0.0042
DOB	0.0030 ↓73.3%	0.0014 ↓66.6%
LQG	0.0024 ↓79.7%	0.0008 ↓81.9%
MPC	0.0018 ↓84.8%	0.0006 ↓85.8%

Passive Compensation

Simulation results with 7.3m Antenna

In initial stage



Control method	Max pointing error(°)
PID	0.0161
DOB	0.0049
LQG	0.0033
MPC	0.0016

51.5%

Outline

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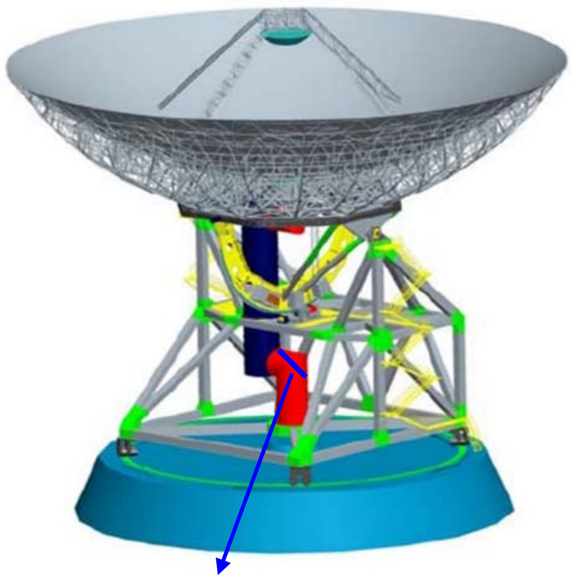
Active Compensation

66m Beam Waveguide Antenna



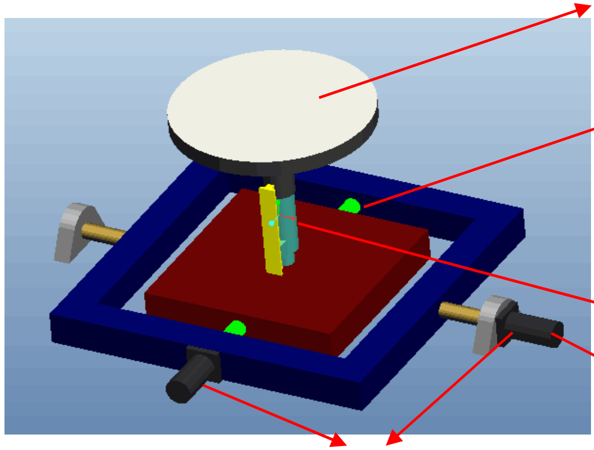
Adjustable Plate Mirror

Moment of Inertia: **2.14×10^{9} kg·m^{2}**

Fundamental frequency: **2.1Hz**

Bandwidth of servo system: **0.6Hz**

Performance for compensating high frequency pointing error ↓



Mirror

Axis of elevation compensation

Electric cylinder

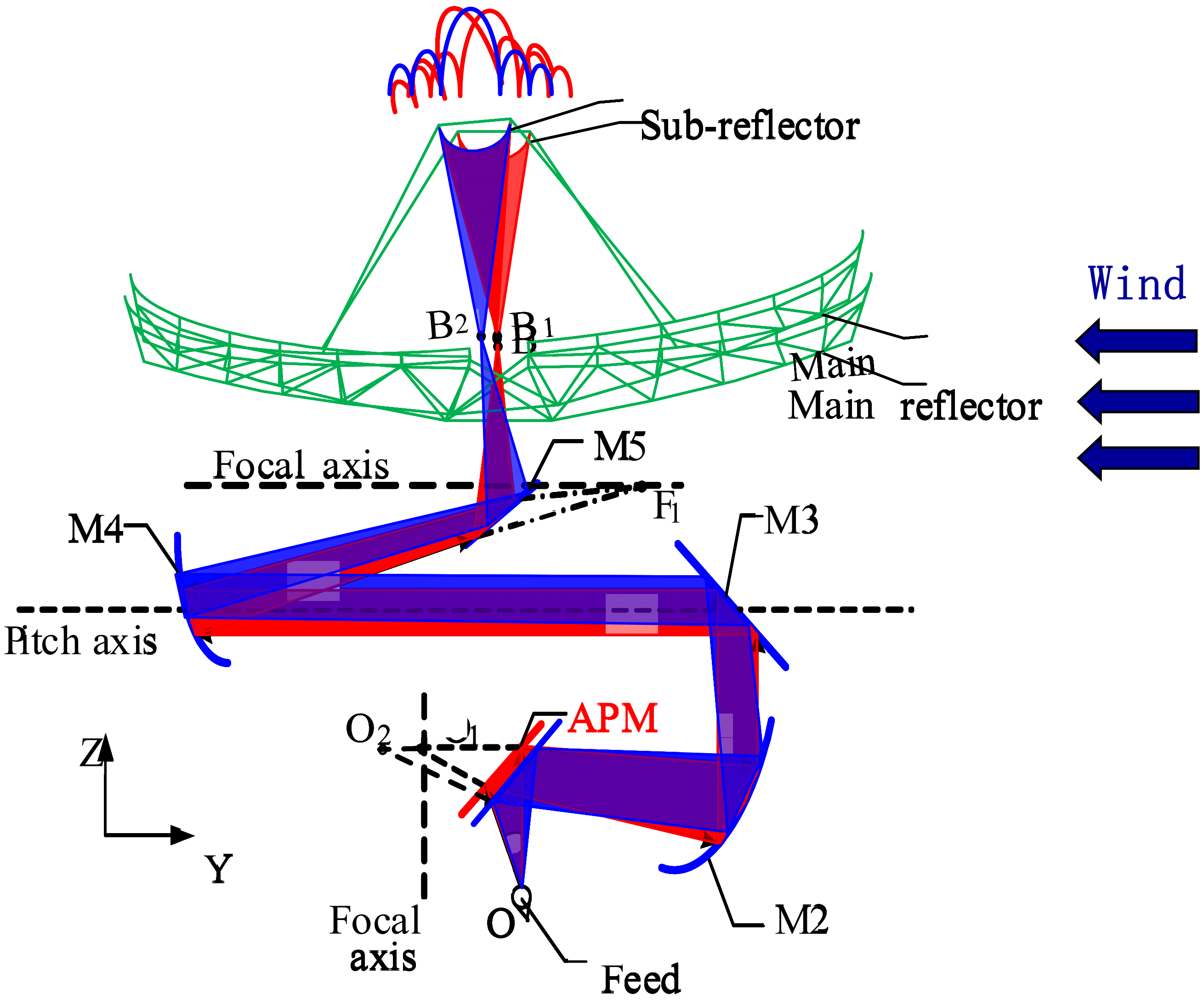
Axis of azimuth compensation

Motor

Improving the pointing accuracy

Active Compensation

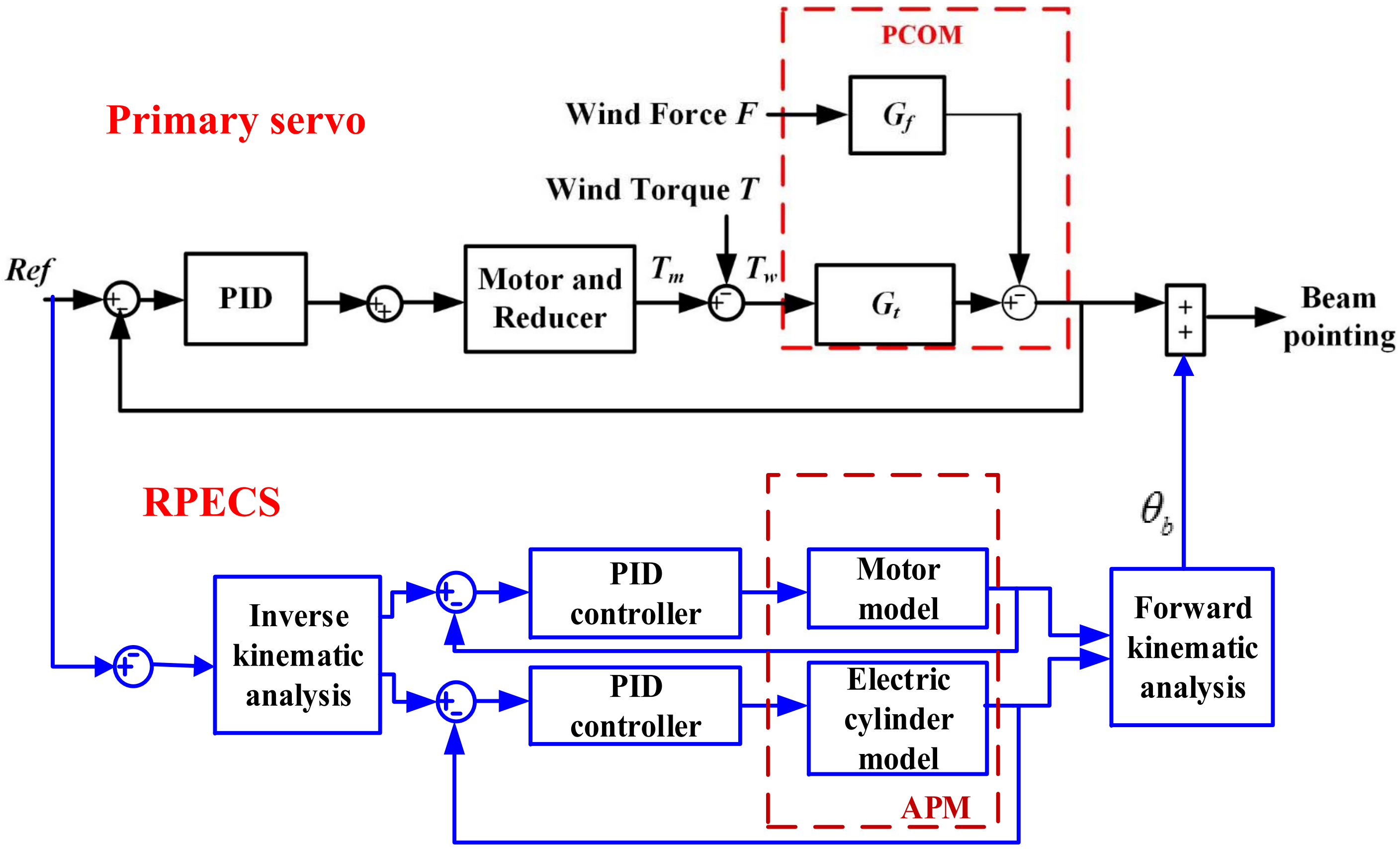
Real-time Pointing Error Compensation System（ RPECS ）



Beam waveguide system

Active Compensation

Real-time Pointing Error Compensation System（ RPECS ）

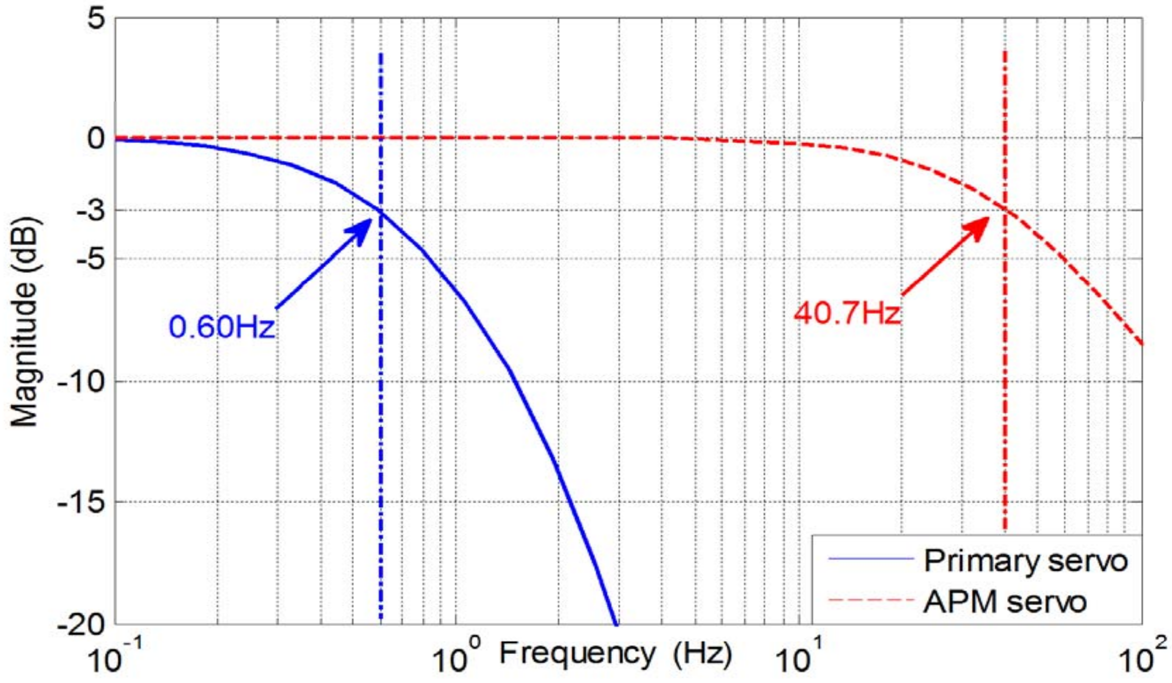


The primary servo subsystem is used to compensate the large-range and slowly-varying error.

The subsystem is used to compensate the final pointing errors with high frequency components.

Active Compensation

Real-time Pointing Error Compensation System（ RPECS ）



The comparison of the bandwidth between the primary servo and the APM servo

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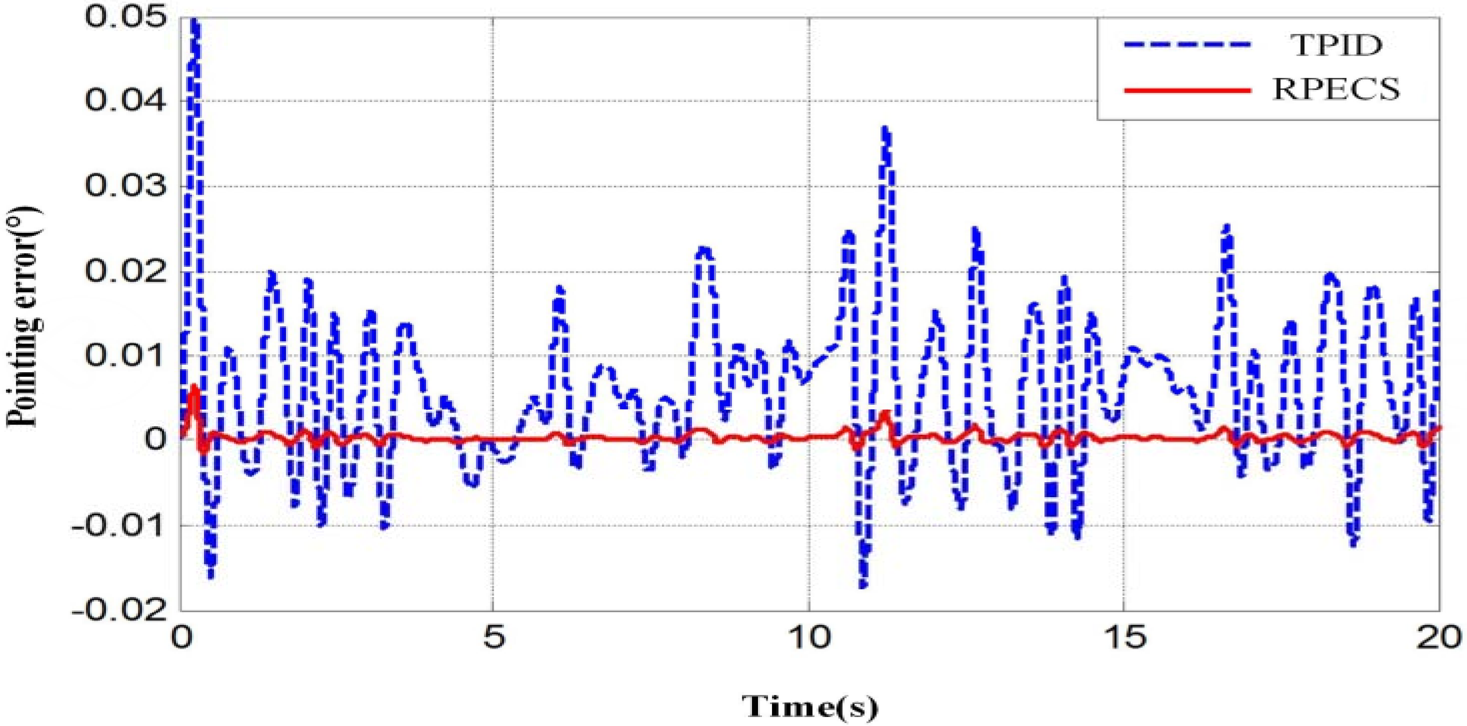
Active Compensation

The compensation effect under a wind speed of 10m/s:



Control method	Max pointing error(°)	RMS pointing error (°)
TPID	0.0368	0.0091
RPECS	0.0020	0.00067
	94.6%	92.7%

Meet the requirement

Jie Zhang, Jin Huang* and Shuangfei Wang et al., An active pointing compensator for large beam waveguide antenna under wind disturbance, *IEEE/ASME Trans. Mechatronics*, 2016, 21(2): 860-871.

Outline

- Motivation
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- Mechatronics Design
- **Conclusions**

Conclusion

The wind effect on pointing accuracy for large antenna is analyzed, and a pointing control-oriented model is presented.

Several Passive pointing error compensation is proposed, which improve the pointing performance effectively.

An active compensation method is put forwarded, in which the high frequency disturbance can be rejected with a fast and high accuracy plate mirror.

These wind disturbance compensation methods can be applied to newly developed large reflector antennas and control system upgrading for those in operation with a low cost hardware, for an improved pointing performance.

Thank you!