# Unifying slow and fast orbit feedback systems…?

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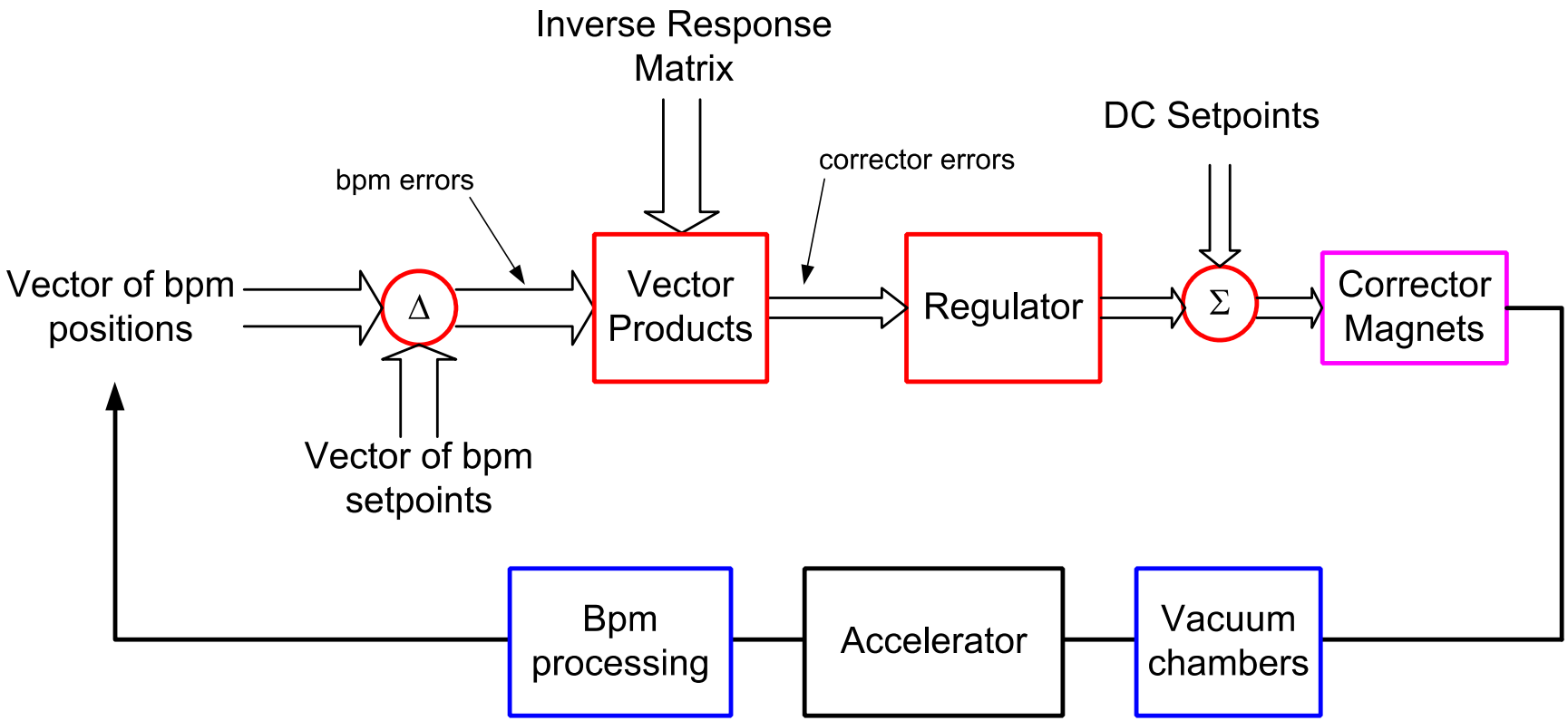
APS User Meeting

9th May, 2013

- Problem statement
- Impact of corrector dynamics on the response matrix equation
- Some different approaches to unification
- Is there an algebraic solution?
- Wrap-up

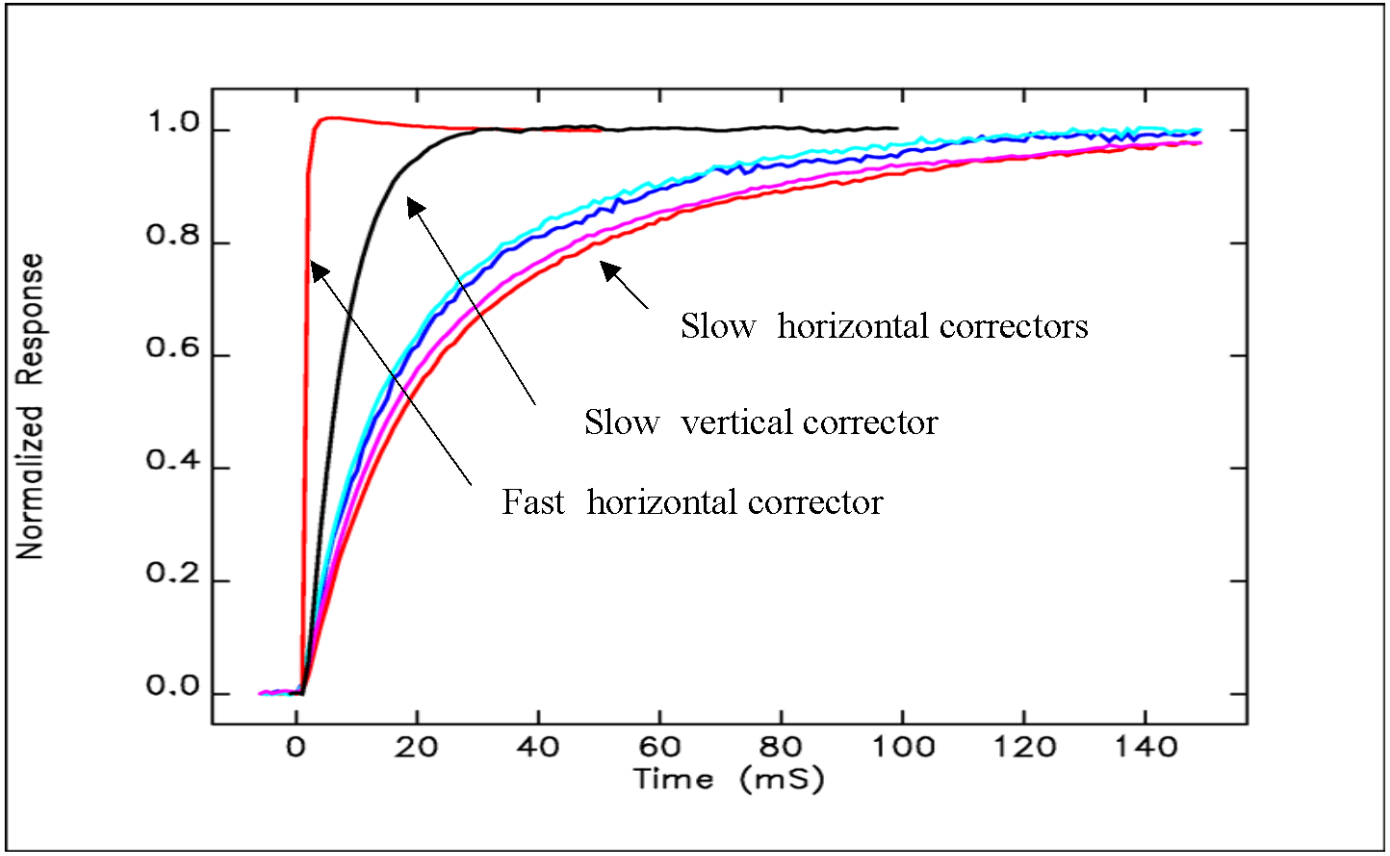
# The dynamic global orbit feedback algorithm



# Measured step responses of APS corrector magnet fields

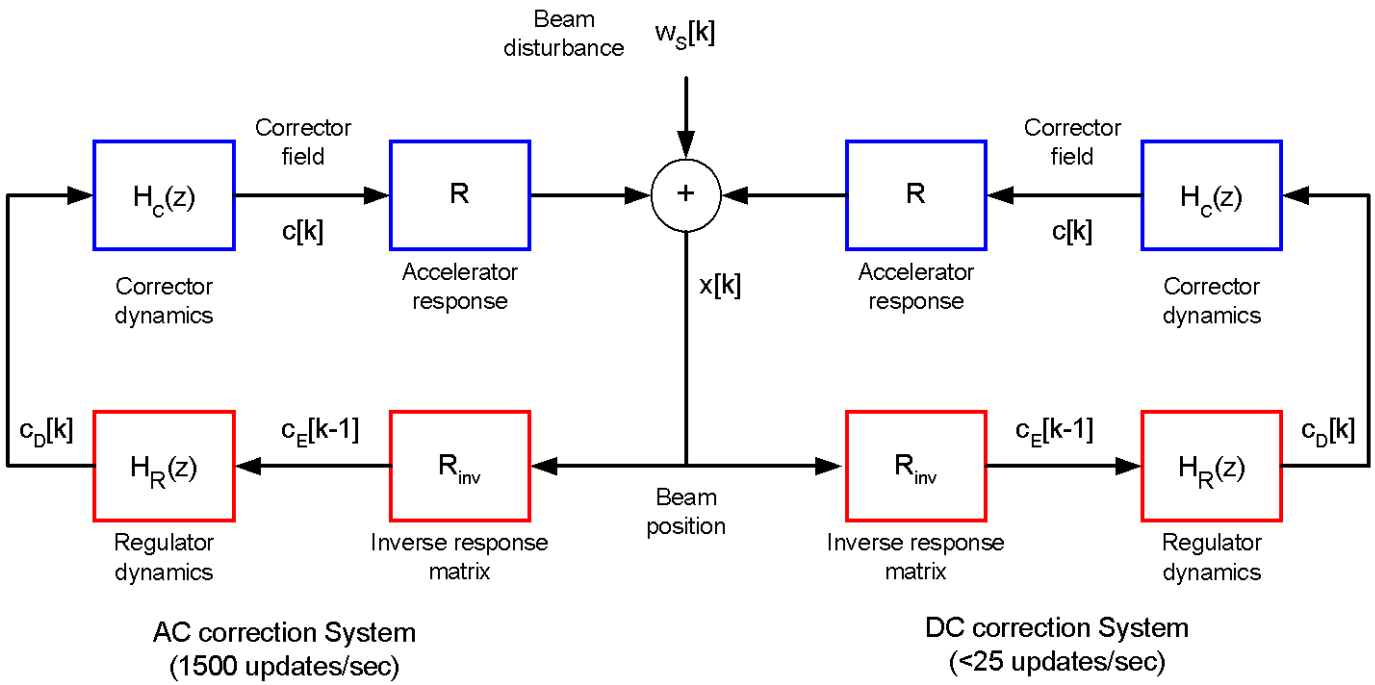
Step responses of the power supplies and magnets are the same in all cases

Overall responses of each corrector family are dominated by eddy-current effects in the vacuum chambers. Effects are different for each family.



# Block diagram of combined DC and AC systems (no overlap compensation)

Both systems attempt to correct the same orbit motion within the frequency band where they are both effective.



# Rationale for unifying fast and slow correctors in the APS orbit feedback system

- **Time domain goal**
  - Wide correction bandwidth
- **Spatial domain goal**
  - Highest precision of orbit correction at the x-ray source points

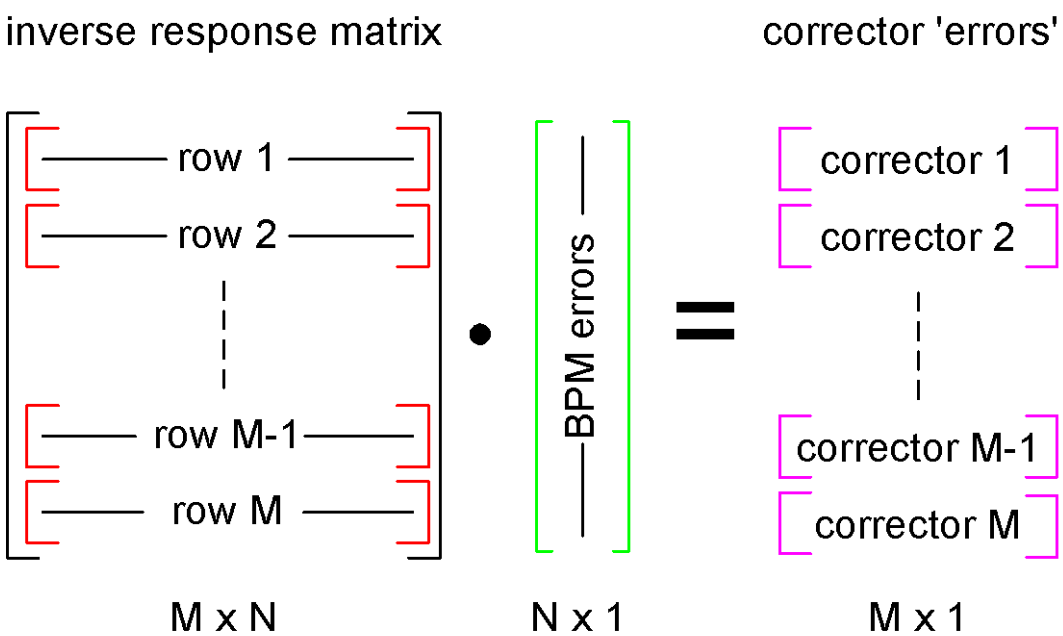
- **But if all correctors are treated as equivalent:**
  - Cannot achieve spatial precision using just the 38 fast correctors
  - Cannot achieve wide bandwidth if we include the slow correctors
- **Compromise goal**
  - good spatial correction at low frequencies
  - High frequency correction but with reduced spatial accuracy

ange in bpm readings for a

unit change in a given corrector

# Implementing the orbit correction algorithm

Computation of corrector errors is conveniently separated into a series of ***M*** vector dot-products, one for each of the ***M*** correctors

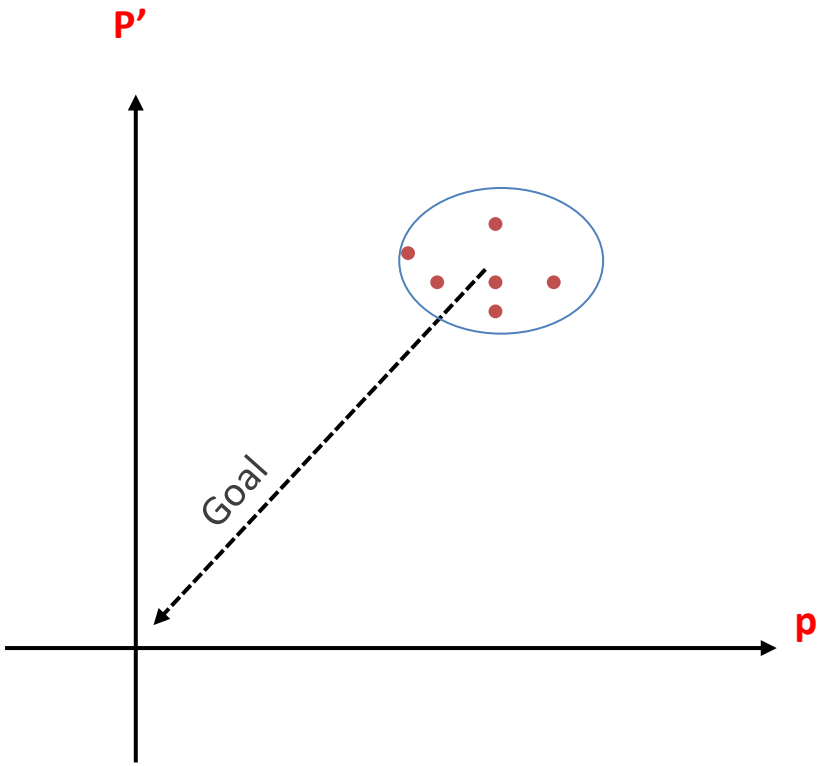



Corrector errors becomes the input to one of ***M*** feedback regulators.

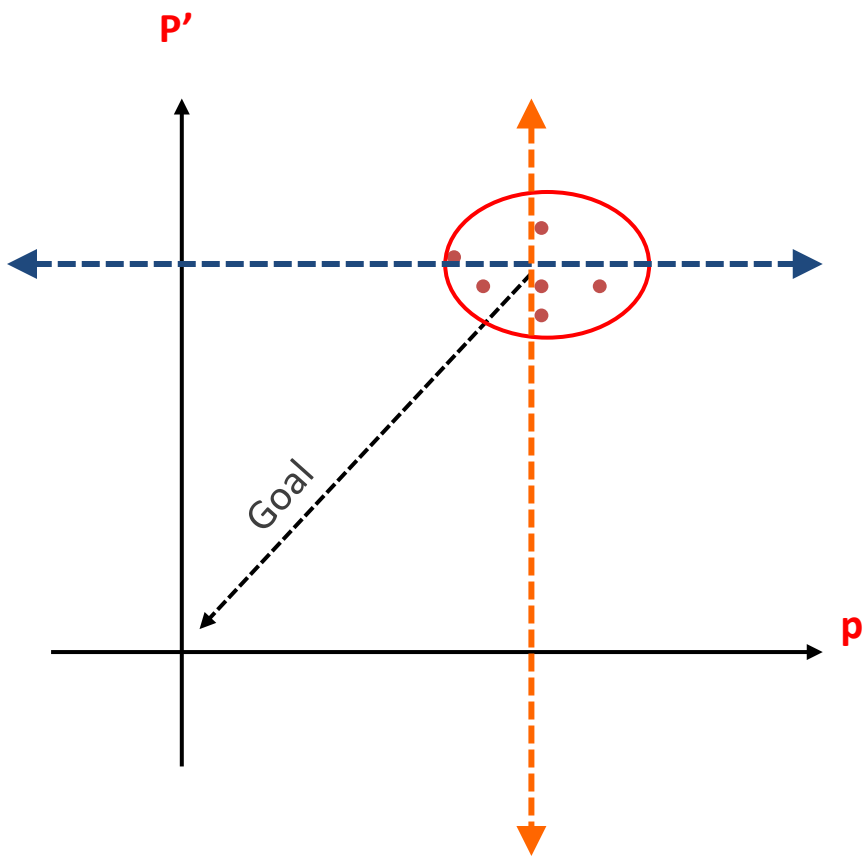
Provided the corrector and bpm dynamics are identical, the feedback loops are independent, and can be implemented as ***M*** single-input / single-output systems.

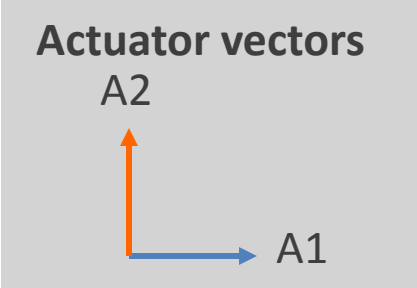
# Made-up linear algebra problem in 2-d space

- Make N measurements of position (p) and angle (p')
- Move RMS of measurement as close as possible to the origin using M actuators



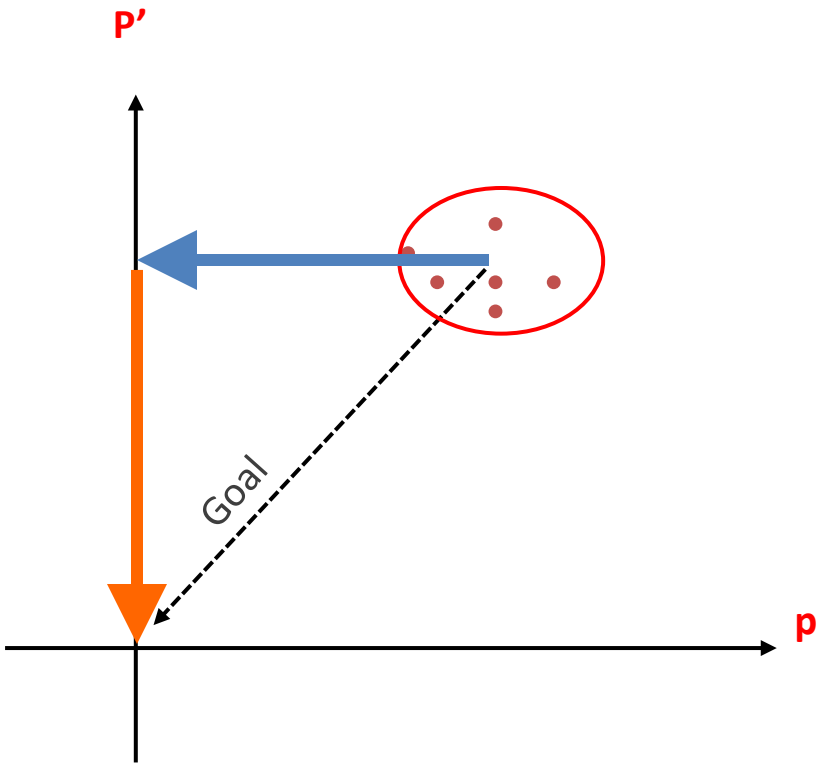
# Two orthogonal actuators

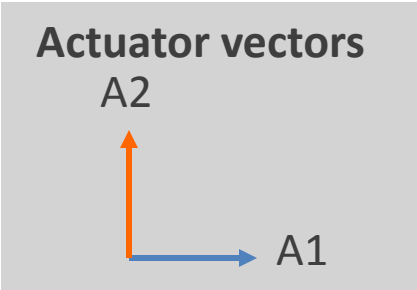


# Two orthogonal actuators

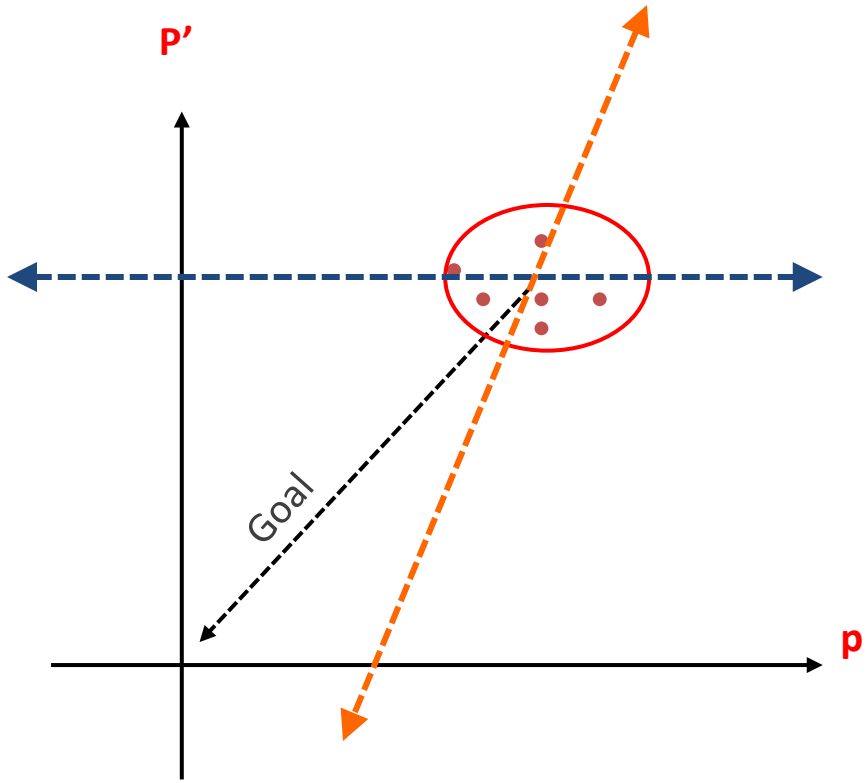
## *Independent solutions for p and p'*

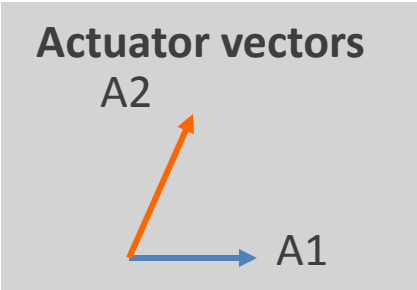


# Two non-orthogonal actuators

- Actuator A1 vector is parallel to p
- Actuator A2 vector has components in p and p’



# Two non-orthogonal actuators

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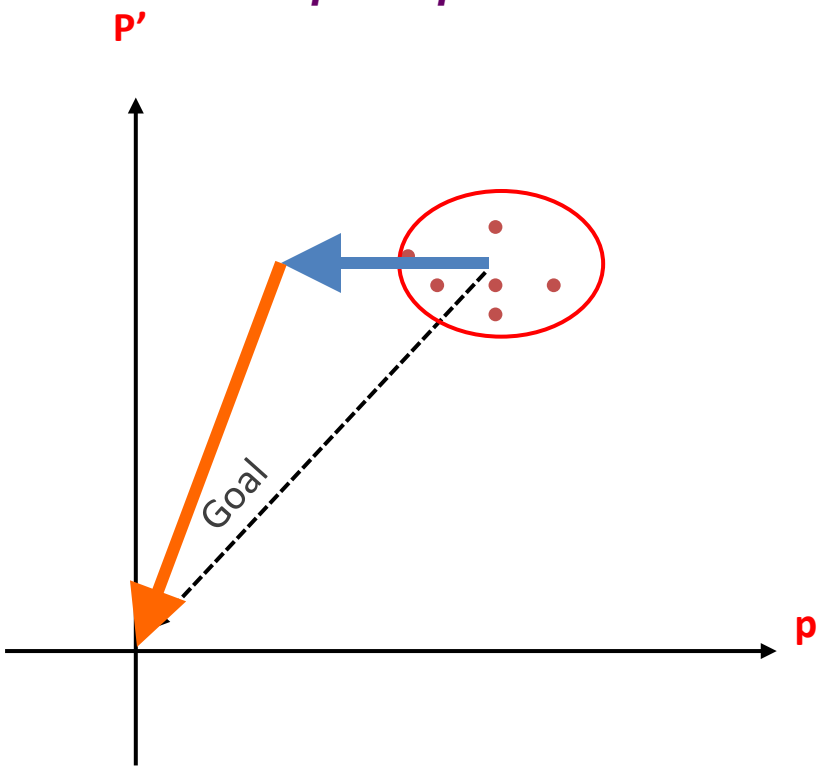
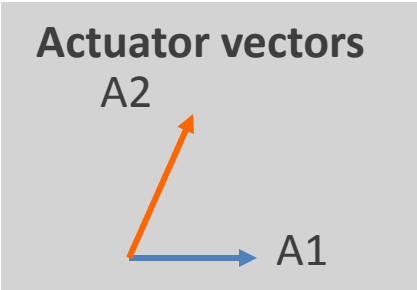
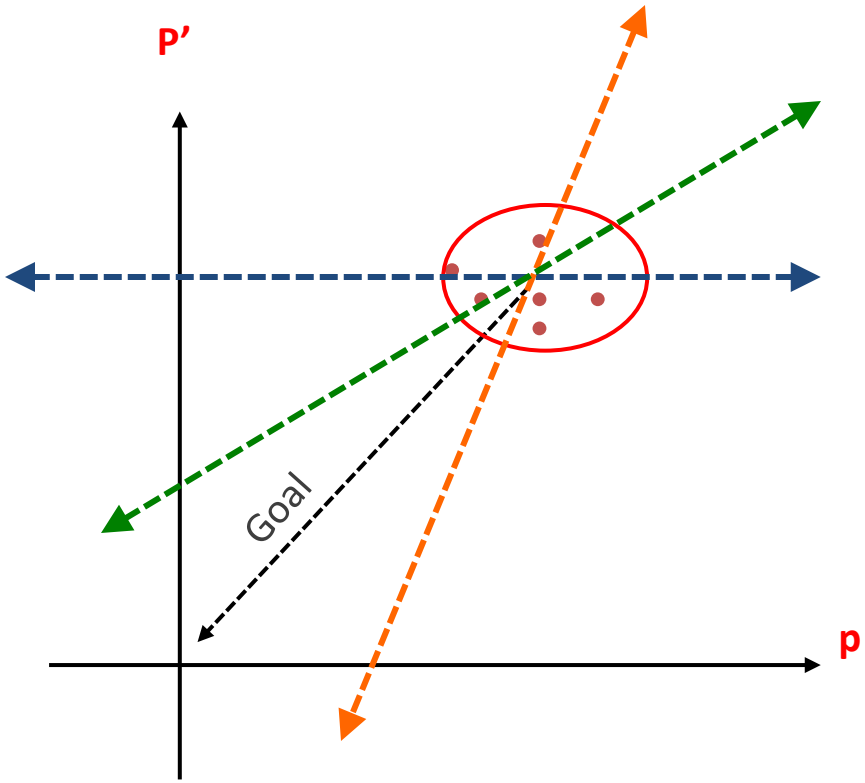
*Coupled solutions for p and p'*

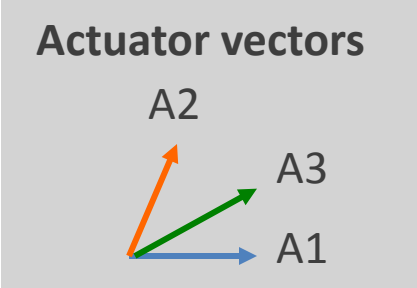


# Three non-orthogonal actuators

- Actuator A1 vector is parallel to p
- Actuators A2 and three vectors have (different) components in p and p’



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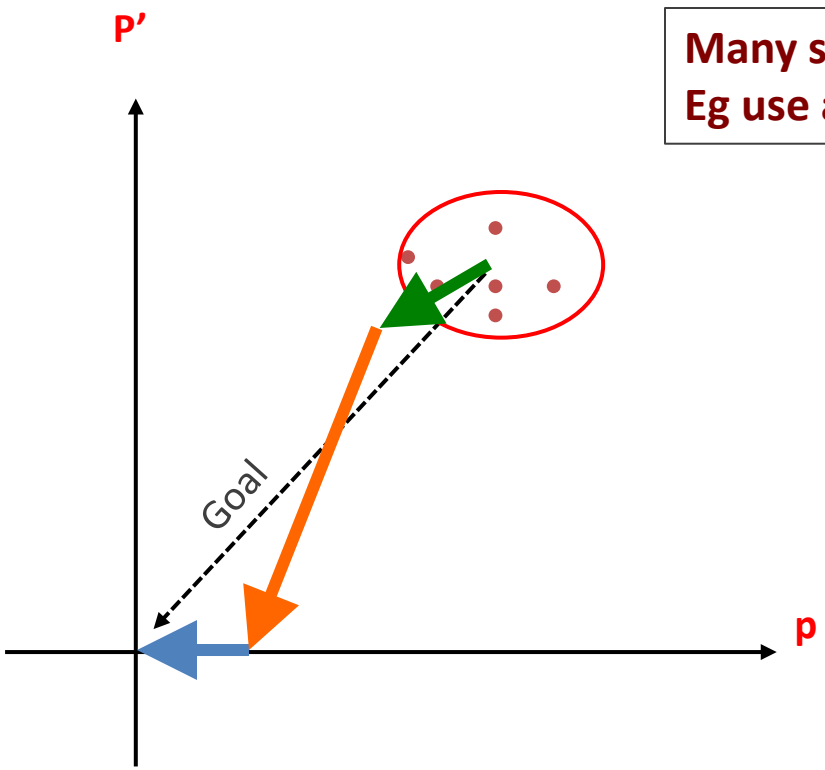
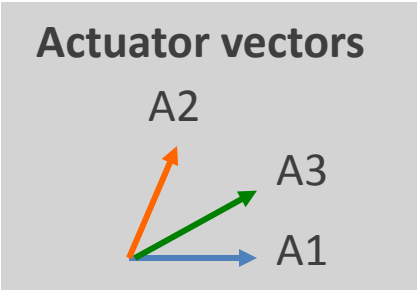
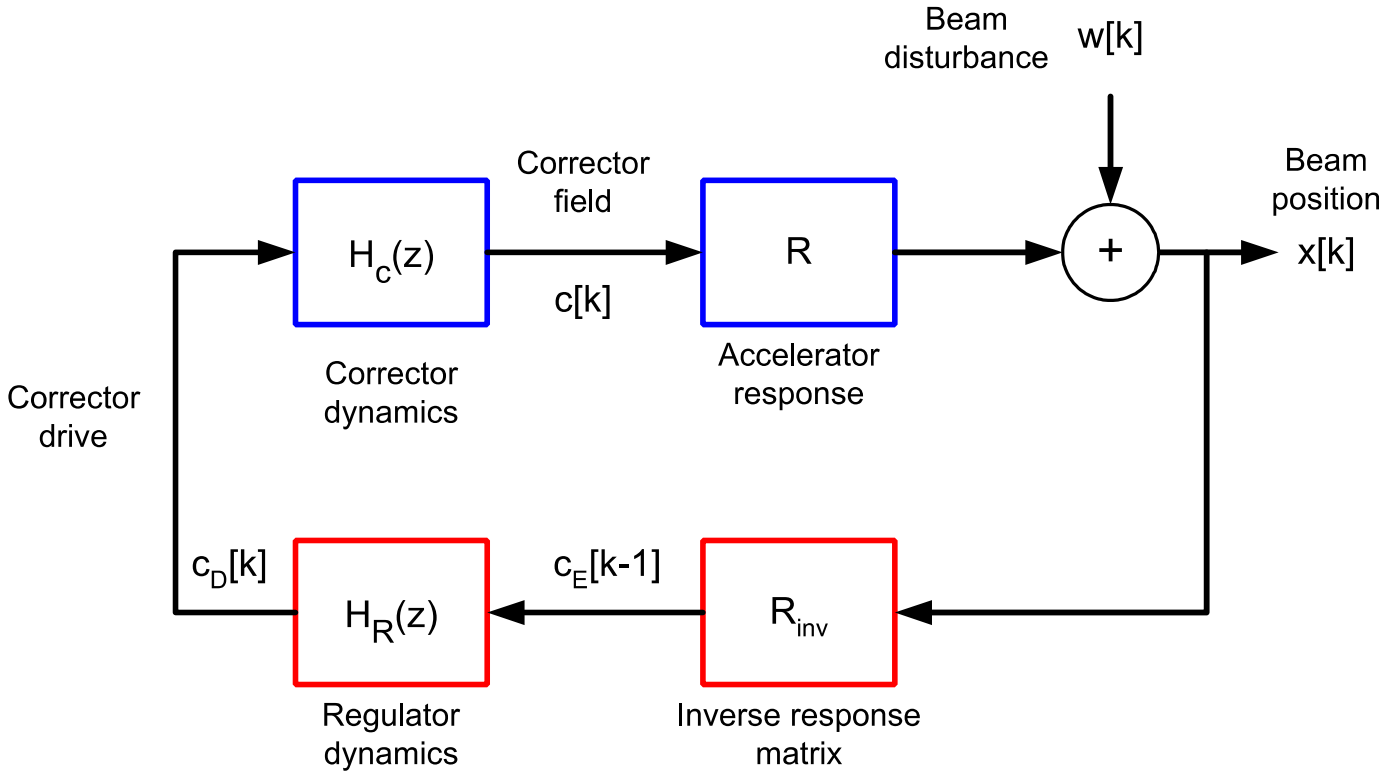



**Many solutions**
**Eg use all correctors in some rms sense**




All very well for static orbit correction, but if the vectors aren't applied simultaneously, the solution is incomplete

# Orbit feedback model revisited (orbit correction to orbit error)




Orbit correction in terms of orbit error…

$$z \cdot X(z) = R \cdot H(z) \cdot R_{inv} \cdot X(z)$$

## Orbit correction to orbit error

- Expand to show diagonal nature of ***$H_c(z)$***

$$\begin{bmatrix} x_1(z) \\ x_2(z) \\ x_3(z) \end{bmatrix} = Z^{-1} \cdot R \cdot \begin{bmatrix} h_{c1}(z) & 0 & 0 \\ 0 & h_{c2}(z) & 0 \\ 0 & 0 & h_{c3}(z) \end{bmatrix} \cdot R_{inv} \cdot \begin{bmatrix} x_1(z) \\ x_2(z) \\ x_3(z) \end{bmatrix} + W(z)$$

Simplest case, no dynamics, and unity gain per corrector channel…

$$\begin{bmatrix} x_1(z) \\ x_2(z) \\ x_3(z) \end{bmatrix} = Z^{-1} \cdot R \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot R_{inv} \cdot \begin{bmatrix} x_1(z) \\ x_2(z) \\ x_3(z) \end{bmatrix} + W(z)$$

so $$R \cdot H(z) \cdot R_{inv} = I$$

## Orbit correction to orbit error with different regulator gains

- Different regulator gains…

$$\begin{bmatrix} x_1(z) \\ x_2(z) \\ x_3(z) \end{bmatrix} = Z^{-1} \cdot R \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot R_{inv} \cdot \begin{bmatrix} x_1(z) \\ x_2(z) \\ x_3(z) \end{bmatrix} + W(z)$$

So, in this case $R \cdot H(z) \cdot R_{inv} \neq I$

- This means that the correction algorithm is rendered partially ineffective when each corrector channel has different dynamics.
- Seen another way, the orbit error is decomposed into ***M*** error vectors (one for each of ***M*** correctors). Only if all error vectors are treated identically does the correction algorithm hold.

# Unification of AC and DC systems
## A few options

1. Let it rip! Have both systems running and independently correcting down to DC
   - UNSTABLE !!

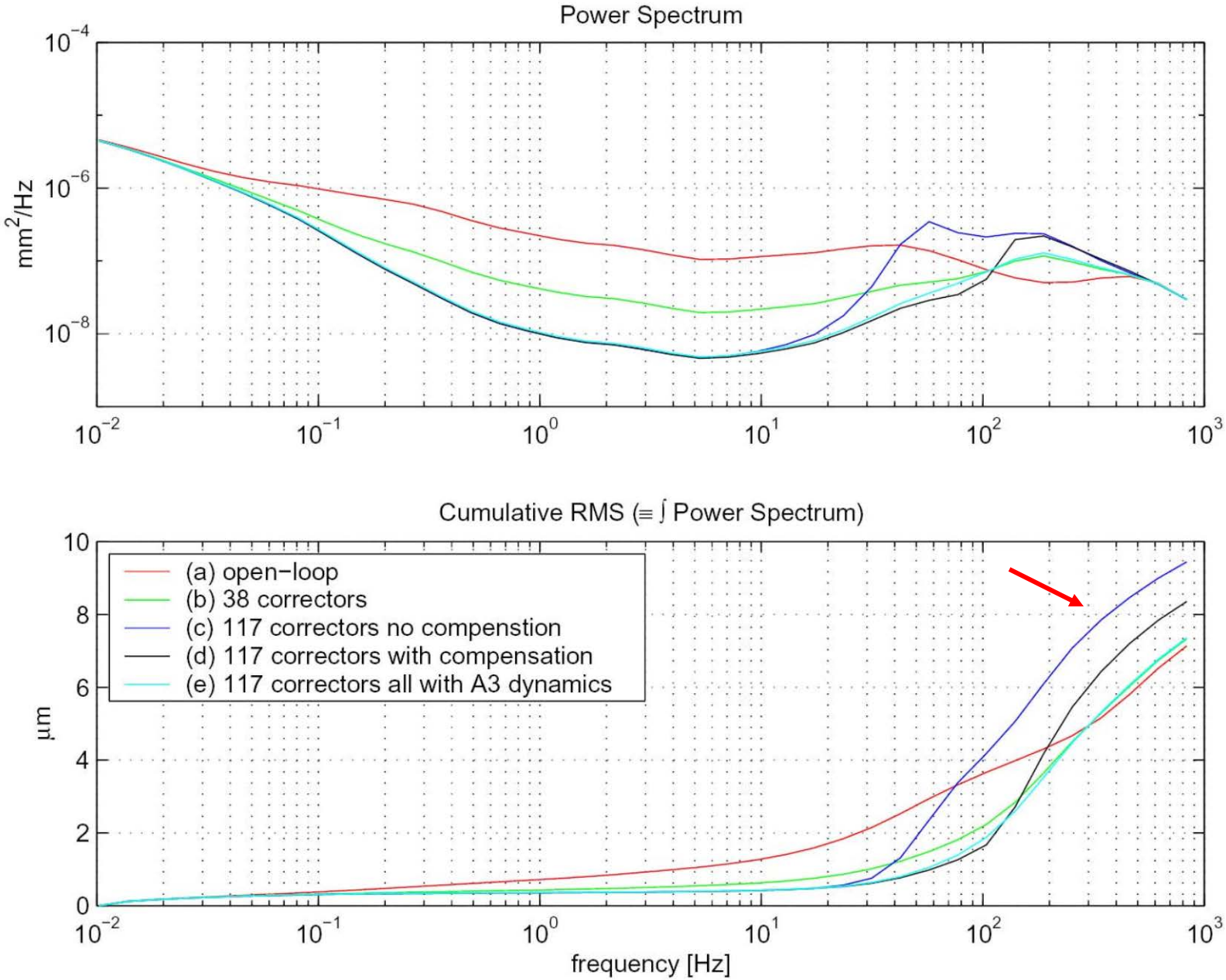
2. Combine the two systems in one response matrix with all correctors
   - At higher frequencies, the slow correctors run out of bandwidth

3. Use compensation network to make slow correctors look like fast correctors

4. Use slow system for DC and fast system for AC (put a high-pass filter at the front of fast system)

5. Algebraic solutions? Fast system corrects from DC, compute response matrix as if the slow system doesn't exist, then use slow system to fix what's left

# Modeled vertical beam motion for various configurations



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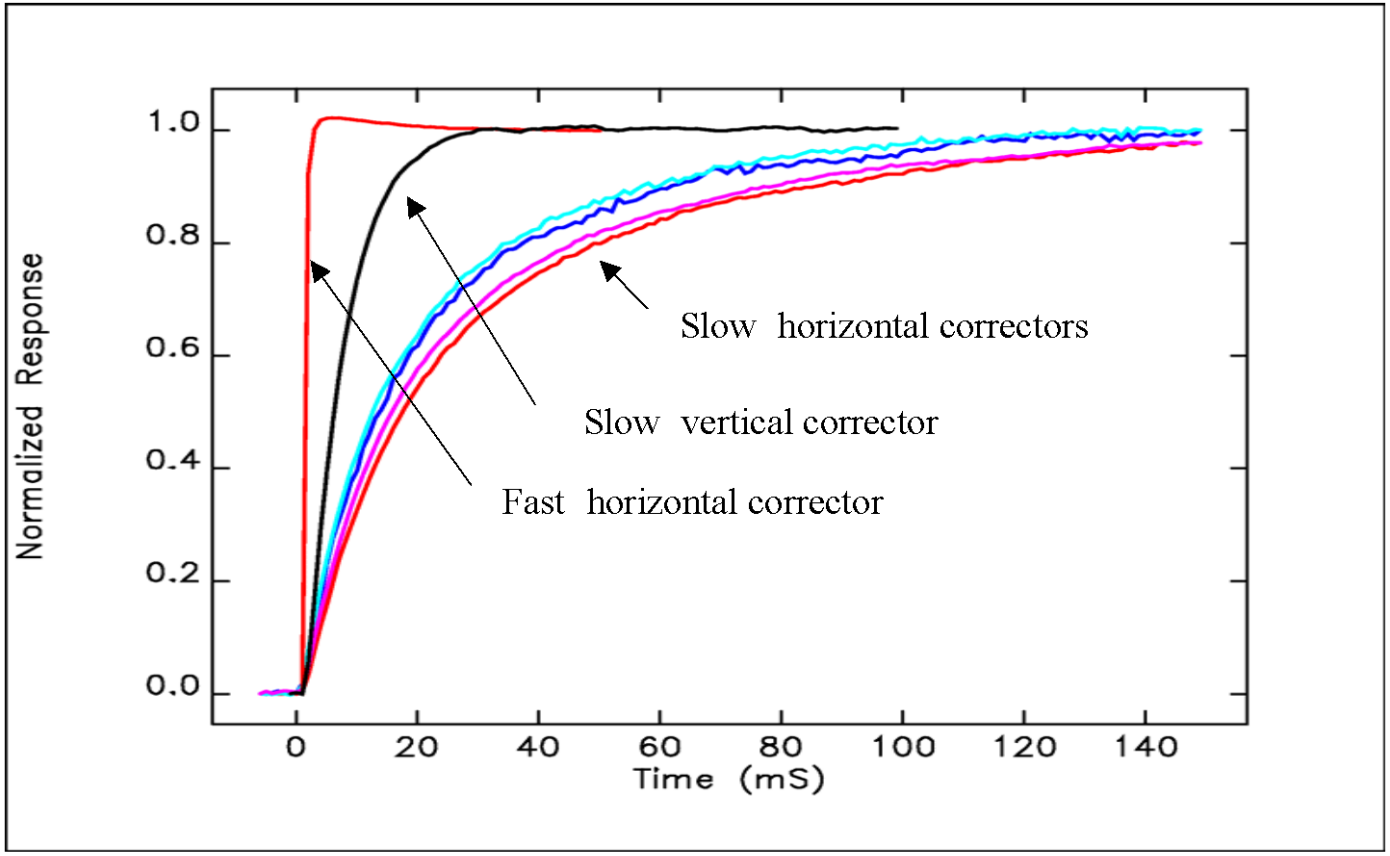
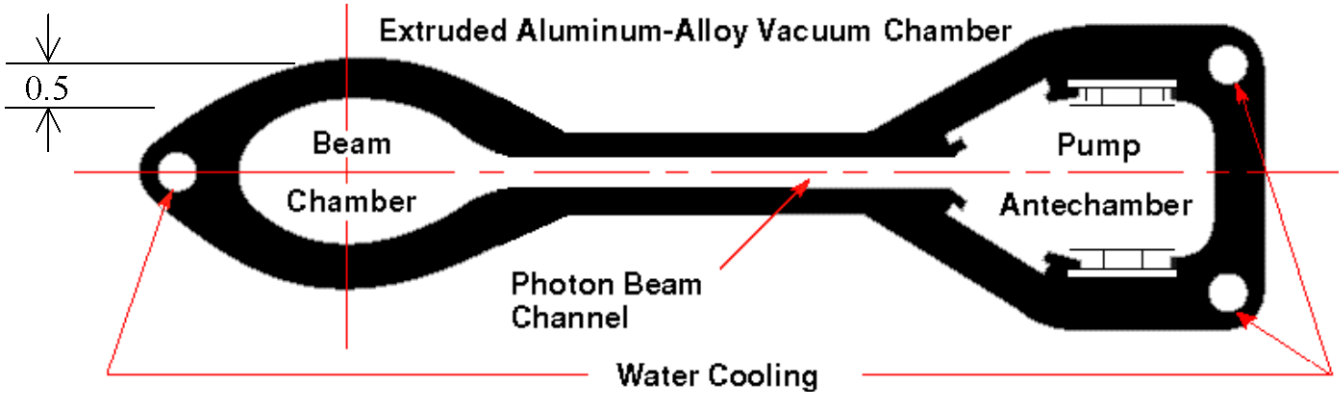


# Effect of vacuum chamber eddy currents

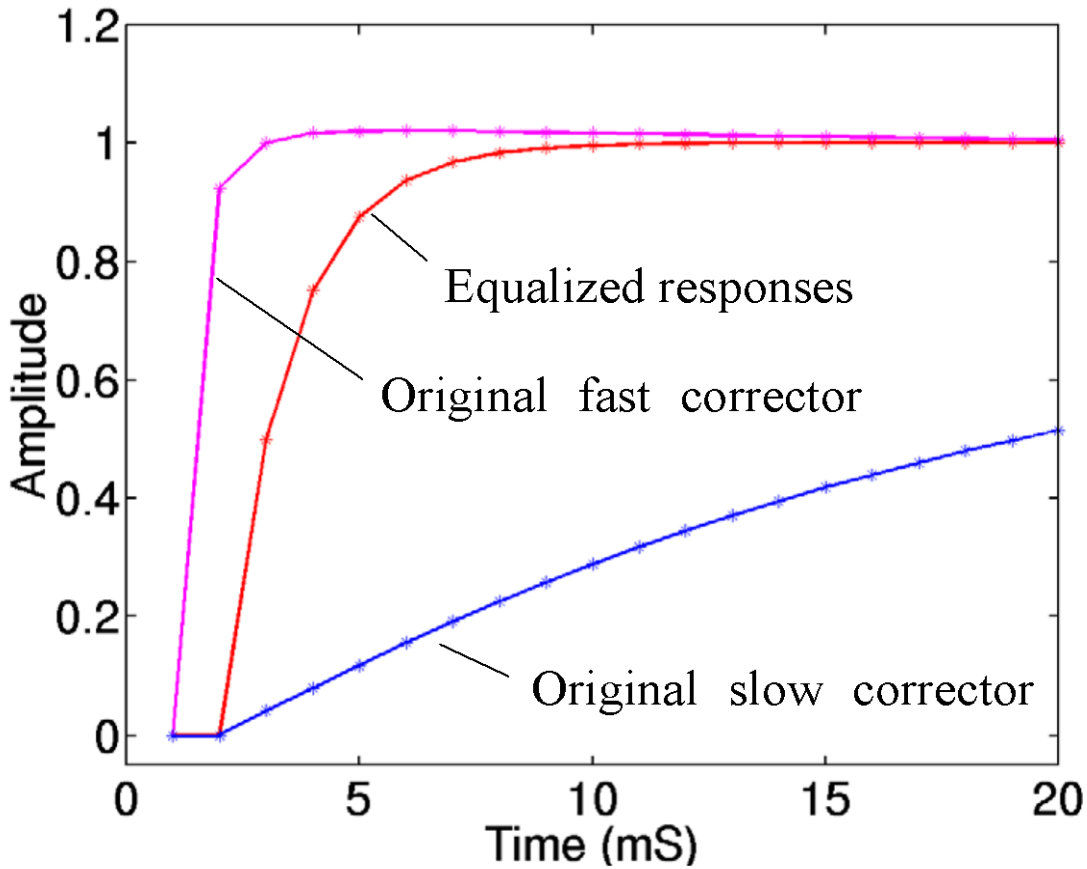
Magnet fields have to penetrate ½ of aluminum in the APS vacuum chamber




This has no impact on DC fields, and therefore on slow orbit correction, but significantly impacts dynamic orbit correction bandwidth for those magnets surrounding the aluminum chamber.

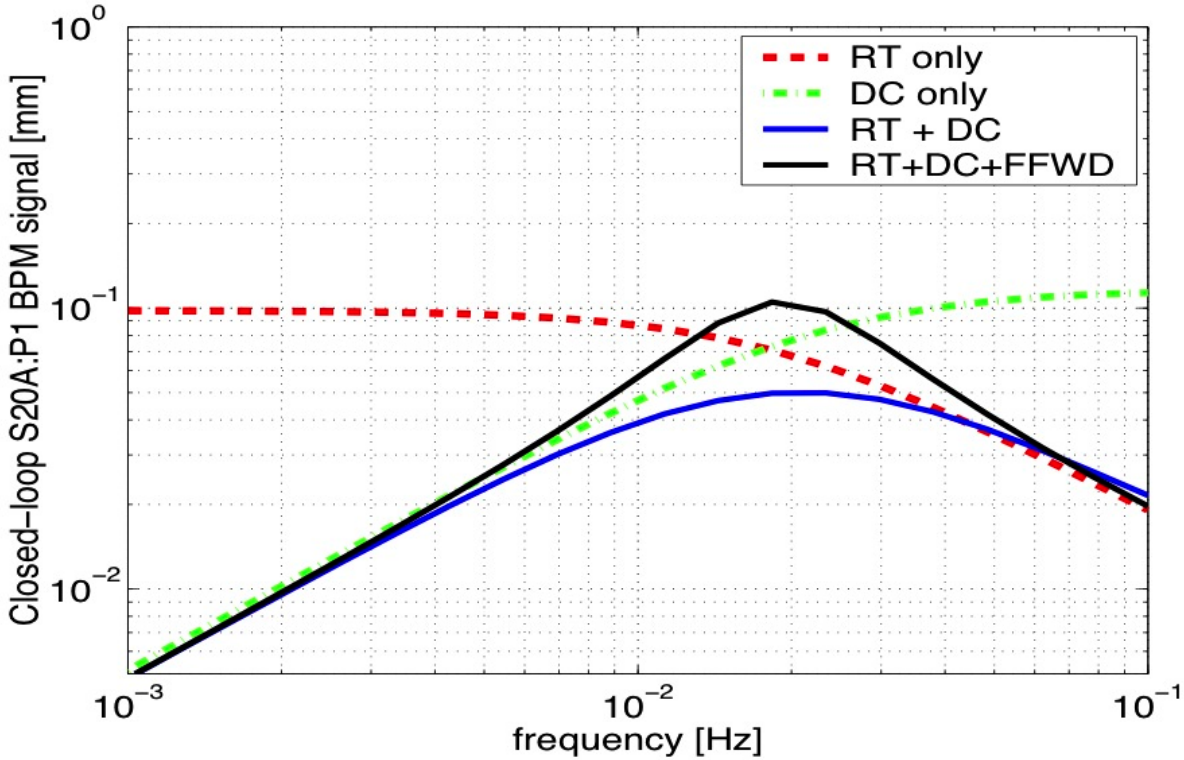
- The eddy-currents introduce a time-delay (not a phase delay)
- Driving the corrector harder does not make the field get through any quicker

# Results of least-squares corrector compensation




Limitation: cannot fix the long eddy-current delay of the slow correctors without violating causality.

# RTFB fixes AC component, slow orbit correction fixes DC orbit (What we do now)



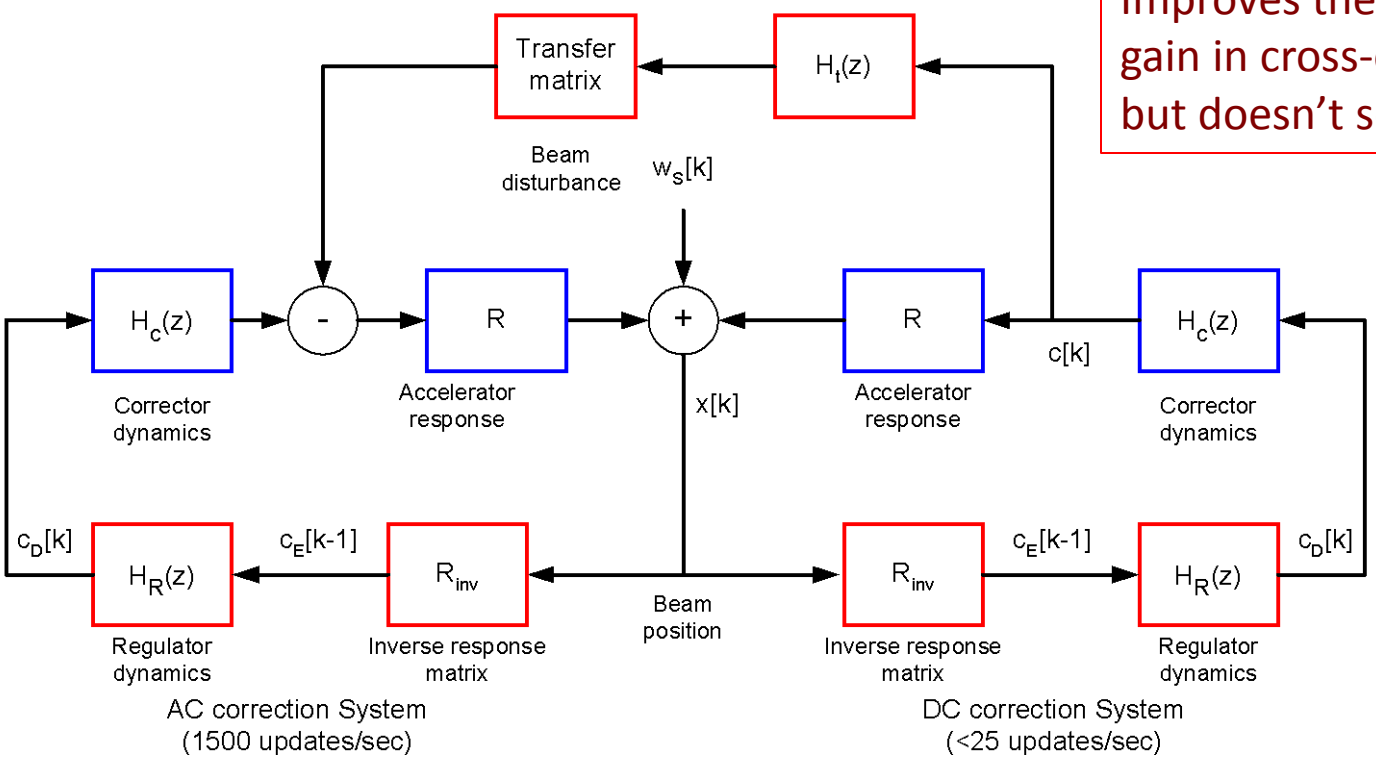

- It works!
- Major limitation: poor attenuation of disturbances in the cross-over region

# Block diagram of combined DC and AC systems (with overlap compensation)

Overlap compensation prevents fighting by introducing a correction factor into one system derived from the action of the other system. Since the two systems use different correctors & bpms and have different dynamics, mappings are required between the two.

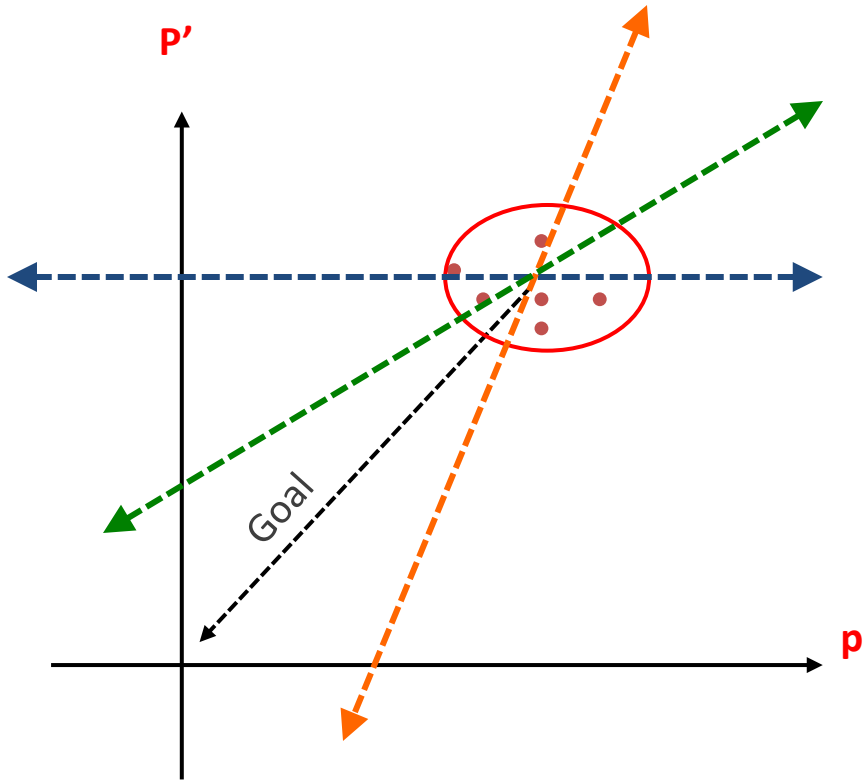
A scheme similar to this is in use at the APS.

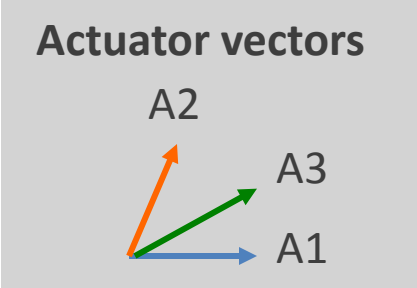
Improves the regulation gain in cross-over region, but doesn't solve the issue



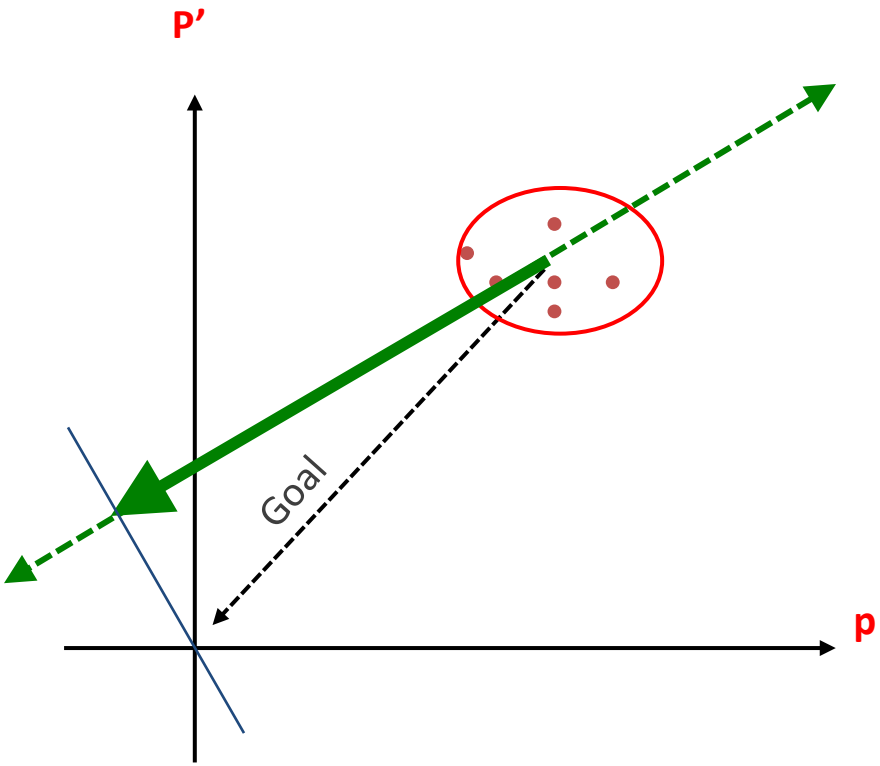

This is what's used at APS now

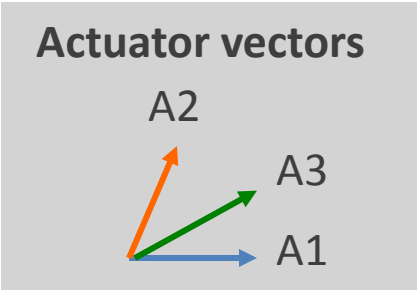
# Slow correction using slow A1 & A2 actuators
# Fast correction using A3 alone…



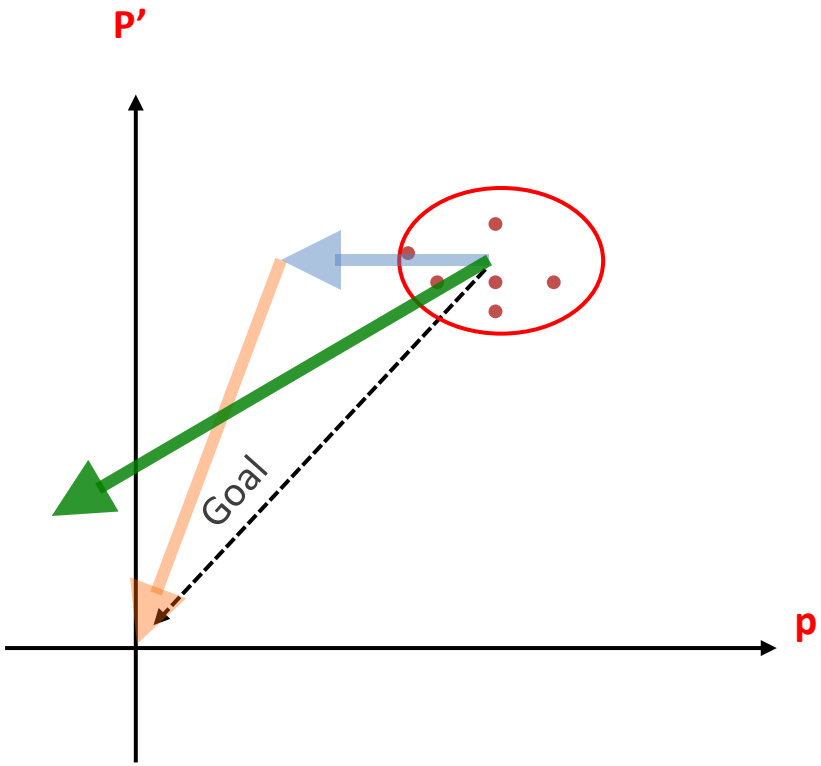



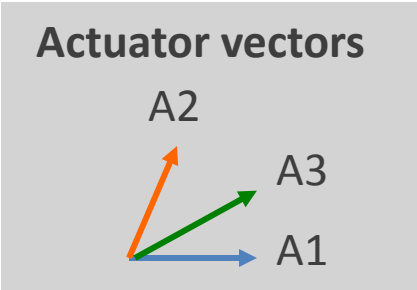
## Slow correction using slow A1 & A2 actuators
## Fast correction using A3 alone…
### Fast: get as close as possible in RMS sense using just A3



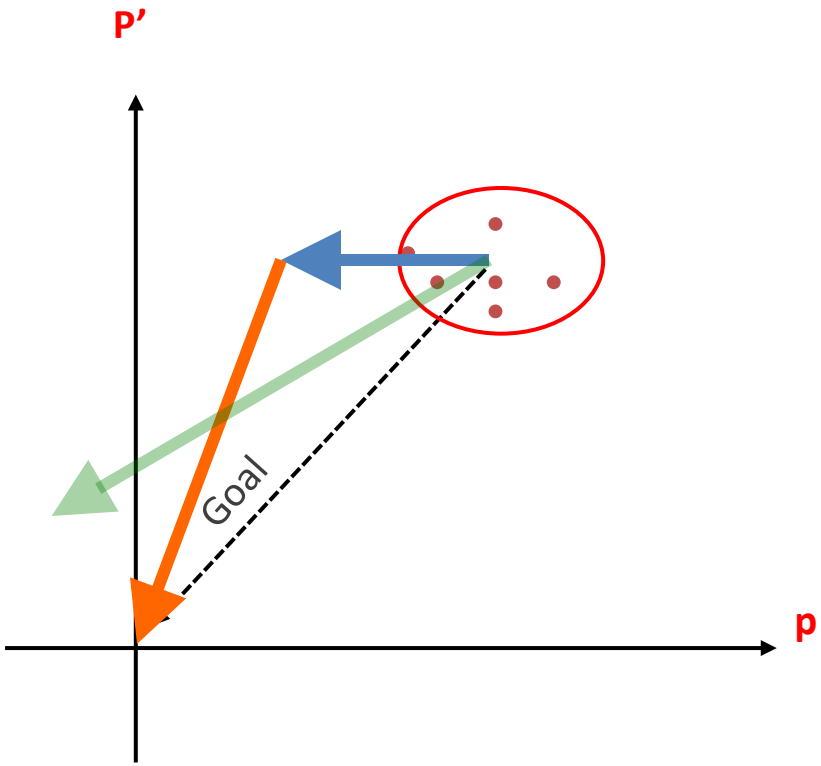



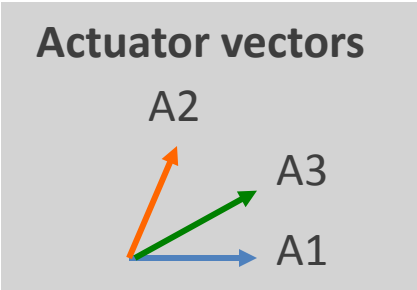
# Migrate to DC correction algorithm using A1 and A2
# Fast correction using A3 ramps down while ramping up slow correction using A1 and A2



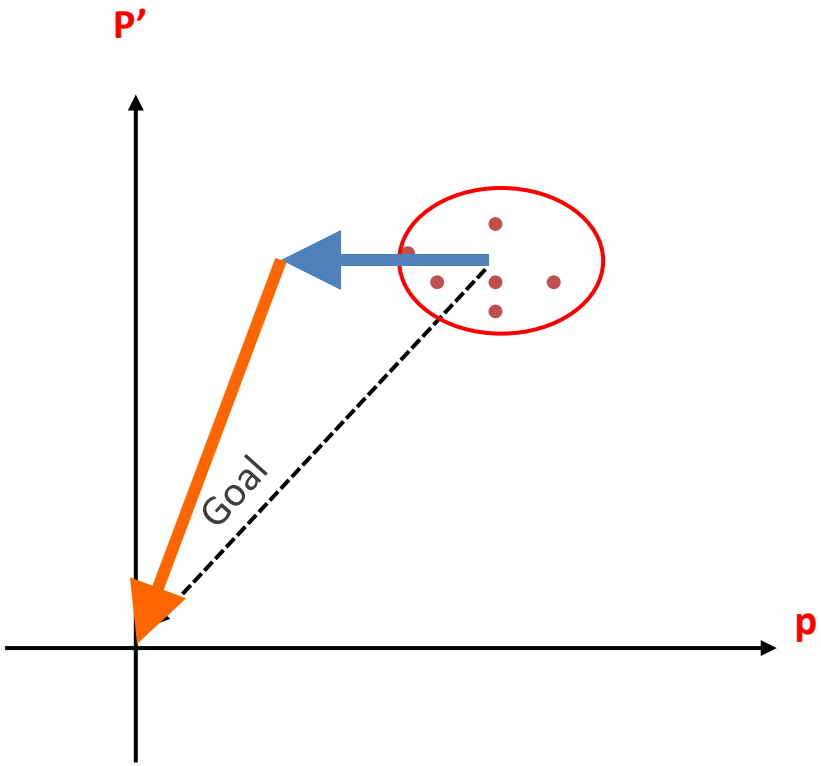



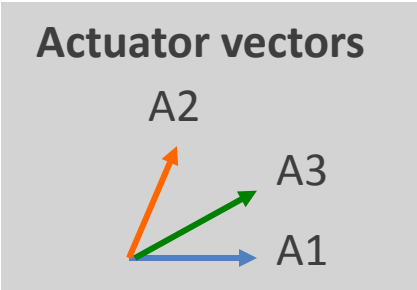
# Migrate to DC correction algorithm using A1 and A2
# Fast correction with A3 ramps down while A1 and A2 solution ramps up



# Finally, only slow correction using A1 and A2 is active

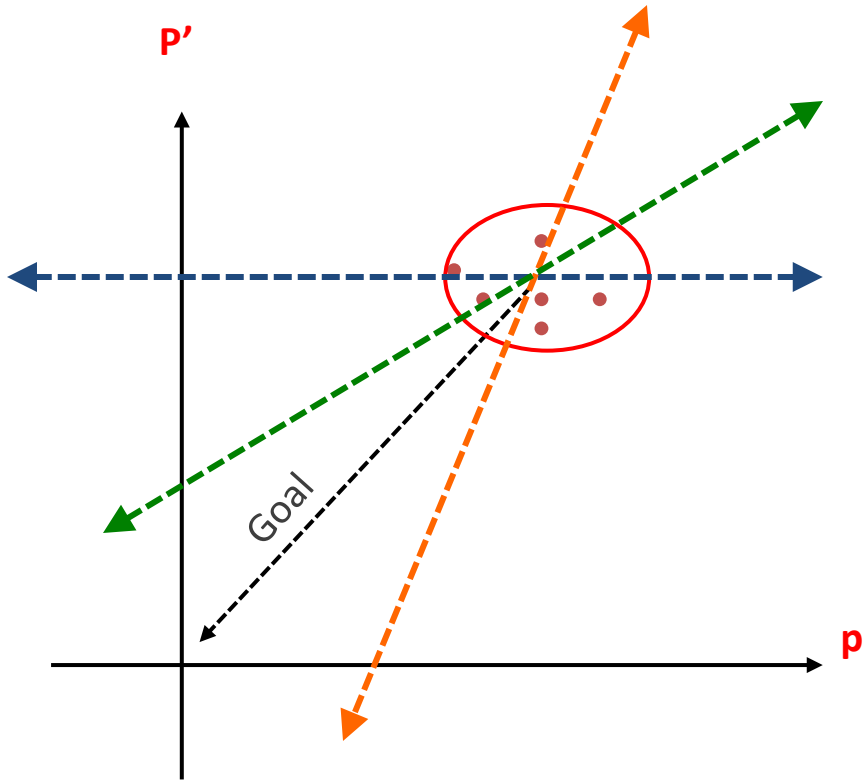


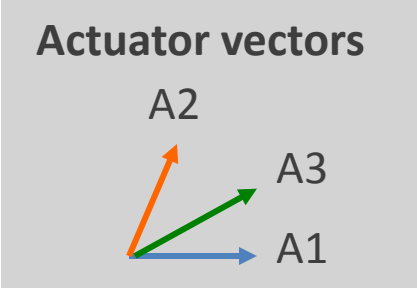



# What about solving the unification problem in the spatial domain? (Algebraic solution)

- Would be ideal!
- Requires orthogonal inverse response matrices for slow and fast systems

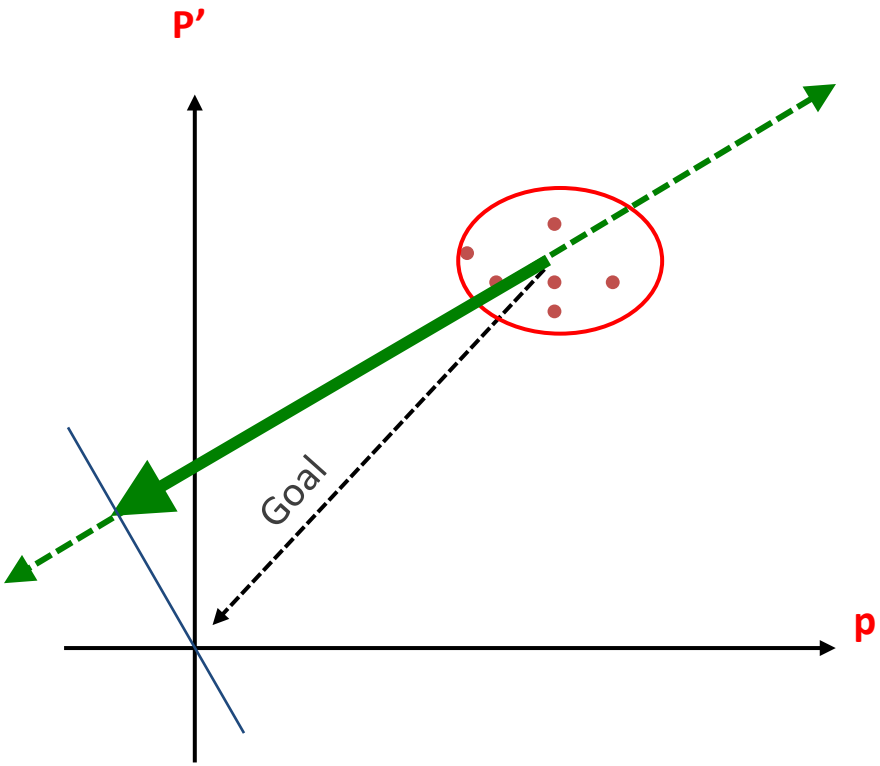
# Slow correction using slow A1 & A2 actuators
# Fast correction using A3 alone…

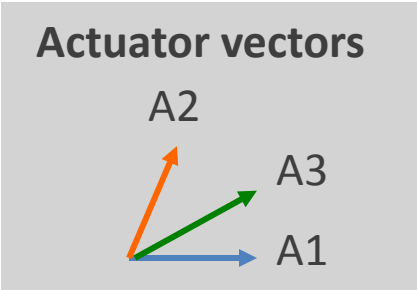


# What if A1 & A2 has slow response, but A3 is fast?

## What about using A1 & A2 to complete the path without turning off A3?



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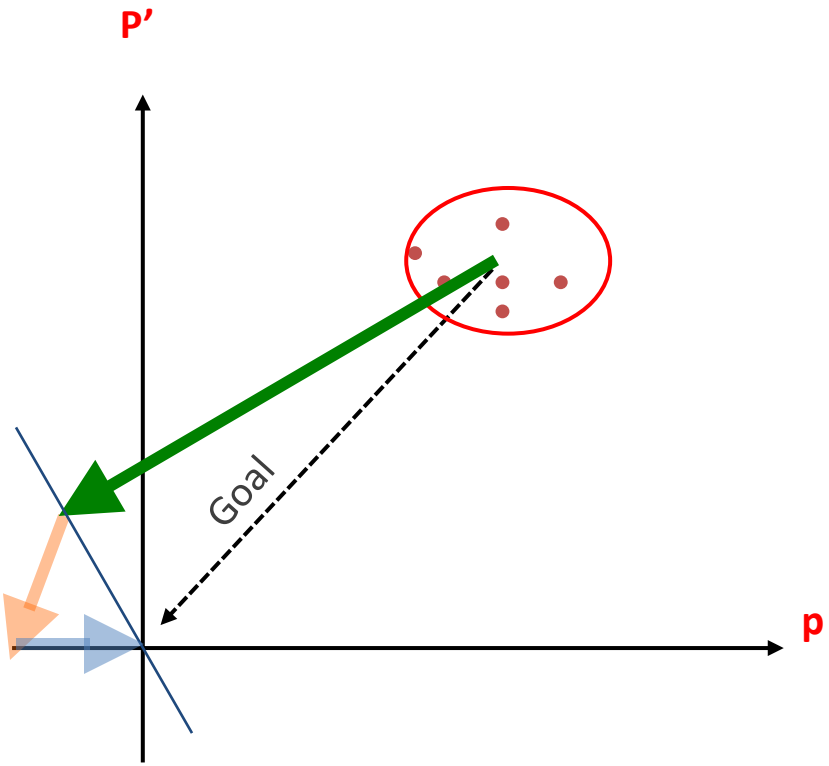


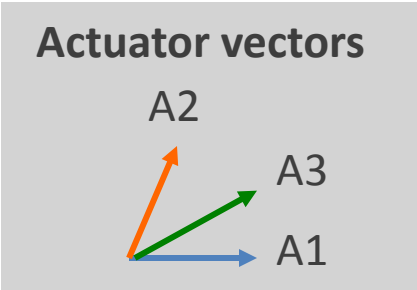

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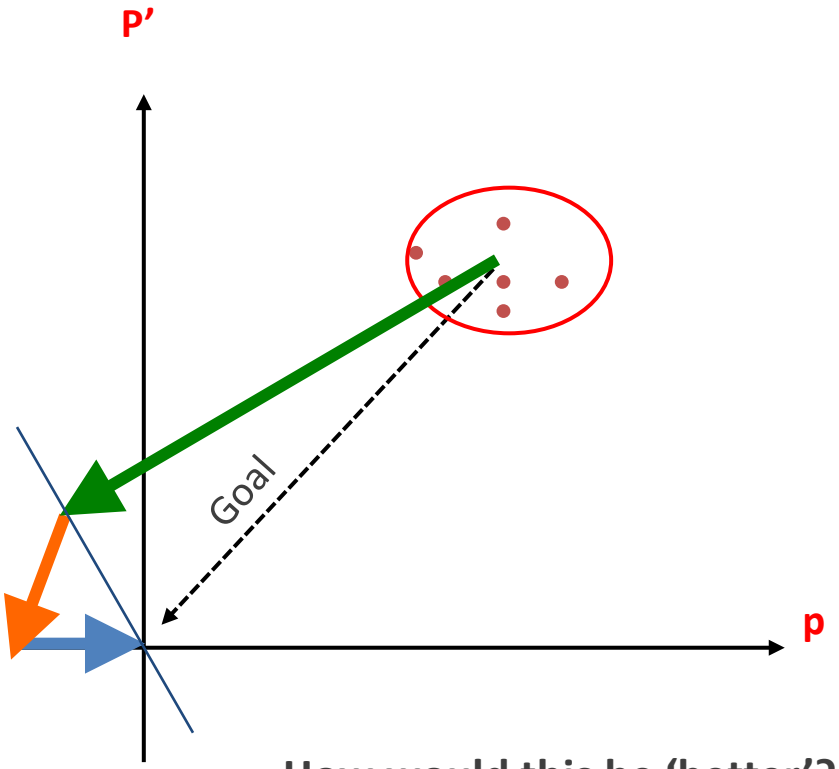


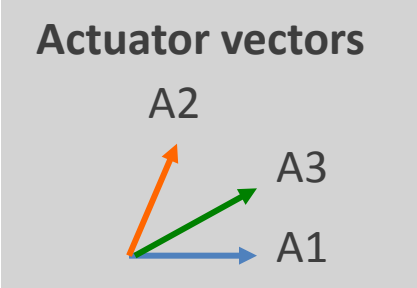


**How would this be 'better'?**

- Eliminates the overlap in frequency space
- Fast system always applies it's optimal corrector strength
- Have the benefit of all three correctors at DC
- At intermediate frequencies, gets incrementally closer to the origin

# Ok, but can we make it work?
## (let's develop the math a little and see where it takes us)

$$\begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{21} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots \\ r_{m1} & r_{m1} & \dots & r_{mn} \end{bmatrix} \cdot \begin{bmatrix} \Delta c_1 \\ \Delta c_2 \\ \dots \\ \Delta c_n \end{bmatrix} = \begin{bmatrix} \Delta p_1 \\ \Delta p_2 \\ \dots \\ \Delta p_m \end{bmatrix}$$

*Slow corr. part* *Fast corr. part*

$$\begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{21} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots \\ r_{m1} & r_{m1} & \dots & r_{mn} \end{bmatrix} \cdot \begin{bmatrix} \Delta c_1 \\ 0 \\ \dots \\ 0 \end{bmatrix}_{fast} + \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{21} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots \\ r_{m1} & r_{m1} & \dots & r_{mn} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ \Delta c_2 \\ \dots \\ \Delta c_n \end{bmatrix}_{slow} = \begin{bmatrix} \Delta p_1 \\ \Delta p_2 \\ \dots \\ \Delta p_m \end{bmatrix}$$

*Equivalently* $$\Delta P = \Delta P_{fast} + \Delta P_{slow} = \left(R_{fast} \cdot \Delta C_{fast}\right) + \left(R_{slow} \cdot \Delta C_{slow}\right)$$

# How to solve…?

Unified inverse RM equation

$$\Delta C = \left(R_{all}\right)^{pinv} \cdot \Delta P$$

We want the fast corrector Inv RM to be as if the slow correctors weren't there

$$\Delta C_{fast} = \left(R_{fast}\right)^{pinv} \cdot \Delta P$$

ie, we're pre-determining a subset of rows of the combined Inv. RM before inverting

$$\begin{bmatrix} \Delta c_1 \\ \Delta c_2 \\ \dots \\ \Delta c_n \end{bmatrix} = \begin{bmatrix} \Delta p_1 \\ \Delta p_2 \\ \dots \\ \Delta p_m \end{bmatrix} \begin{bmatrix} ir_{11} & ir_{12} & \dots & ir_{1n} \\ ir_{21} & ir_{21} & \dots & ir_{2n} \\ \dots & \dots & \dots & \dots \\ ir_{m1} & ir_{m1} & \dots & ir_{mn} \end{bmatrix}$$

# How to solve…?

Plug back into the response matrix equation for the fast correctors alone

$$\Delta p_{fast} = R_{fast} \cdot \left(R_{fast}\right)^{pinv} \cdot \Delta P$$

Plug this back into the combined response matrix equation

$$R_{slow} \cdot \Delta C_{slow} = \Delta P - R_{fast} \cdot \left(R_{fast}\right)^{pinv} \cdot \Delta P$$

Now invert?

$$\Delta C_{slow} = \left(R_{slow}\right)^{pinv} \left[ I - R_{fast} \cdot \left(R_{fast}\right)^{pinv} \right] \cdot \Delta P$$

Form is similar to the overlap compensation scheme

It looks like we should be able to create a single modified IRM for the slow correctors, practical approach is probably a weighted least-squares inversion of combined RM

## *Now Glenn is disappointed because I don't have a final answer or detailed simulation results to show (yet)*

- Has similarities with the overlap compensation approach but is independent of dynamics
- It looks like we should be able to create a single static IRM that can be separately applied in the slow and fast systems
- A practical approach to generating the Inv. RM would likely be a weighted least-squares inversion of the combined RM

# What the best solution for unifying fast and slow feedback systems…?

- Frequency separation with overlap compensation has been good enough so far, but we need to do better
- Compensation network of slow corrector responses doesn't fix the eddy-current-induced delays, but would certainly help

- Probably the optimum solution comprises sub-optimal solutions for slow and fast systems individually (we need a good model of the orbit disturbance characteristics)

- An algebraic solution that orthogonalises fast & slow systems seems feasible – robustness and effectiveness to be studied