Models for Predicting Color Point Stability

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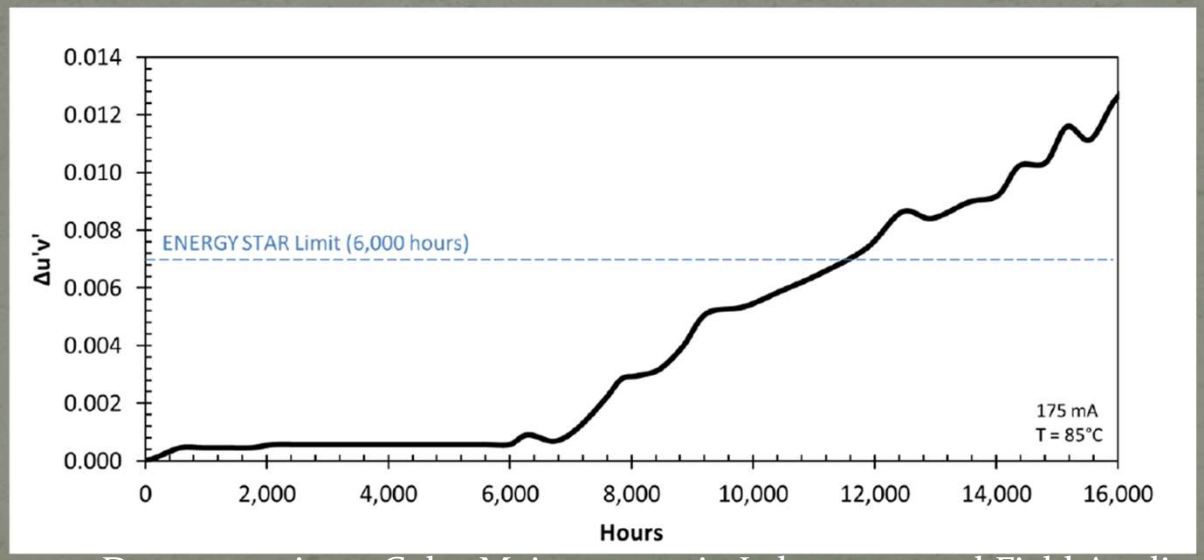
LED Color Point Stability

Current Standard:

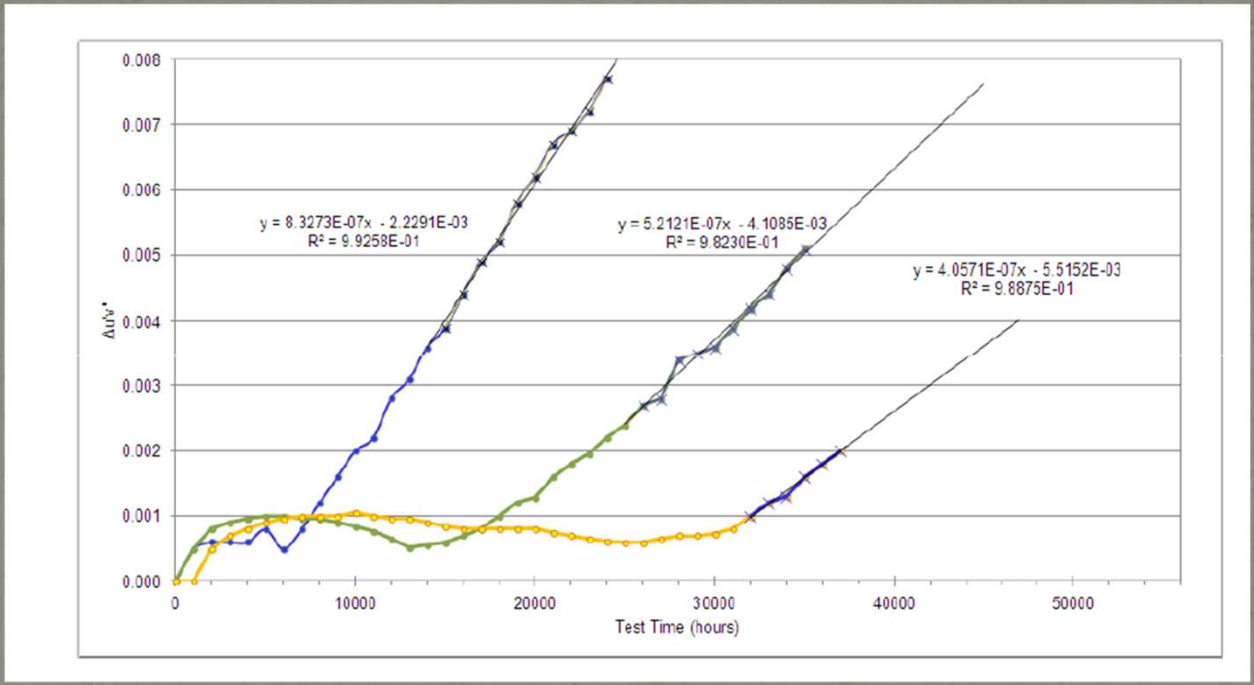
- Energy Star: Δu'v' ≤ 0.007 over 6,000 hours
- This is hardly a standard
- Nor is it adequate



Gateway Demonstrations: Color Maintenance in Laboratory and Field Applications

Linear Extrapolation?

- Could simple linear extrapolation work?

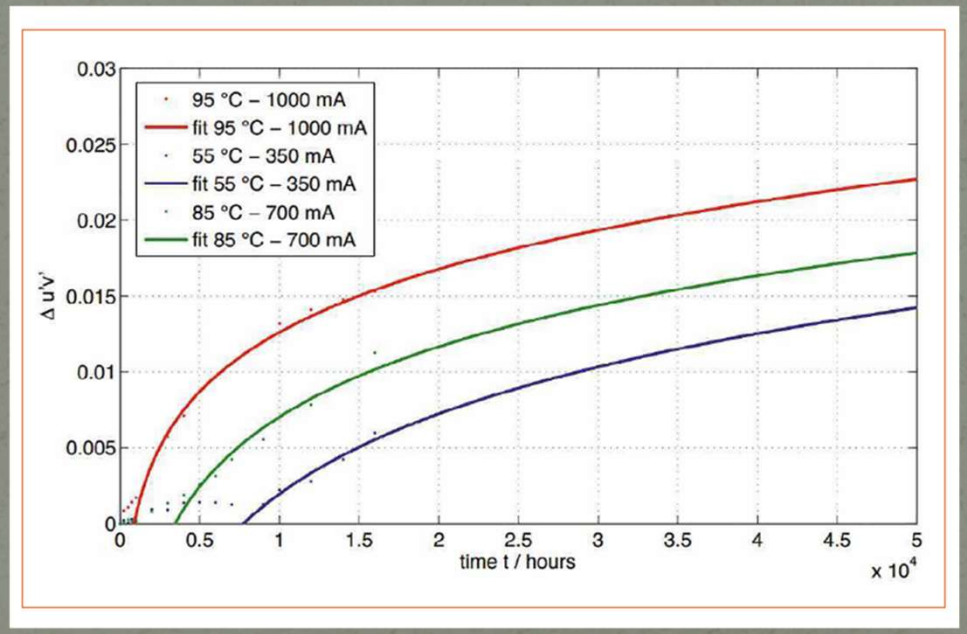


R. Tuttle: LED Package Reliability (Color Point Stability) DOE SSL R&D Workshop 2015

. . . only if we are extraordinarily patient

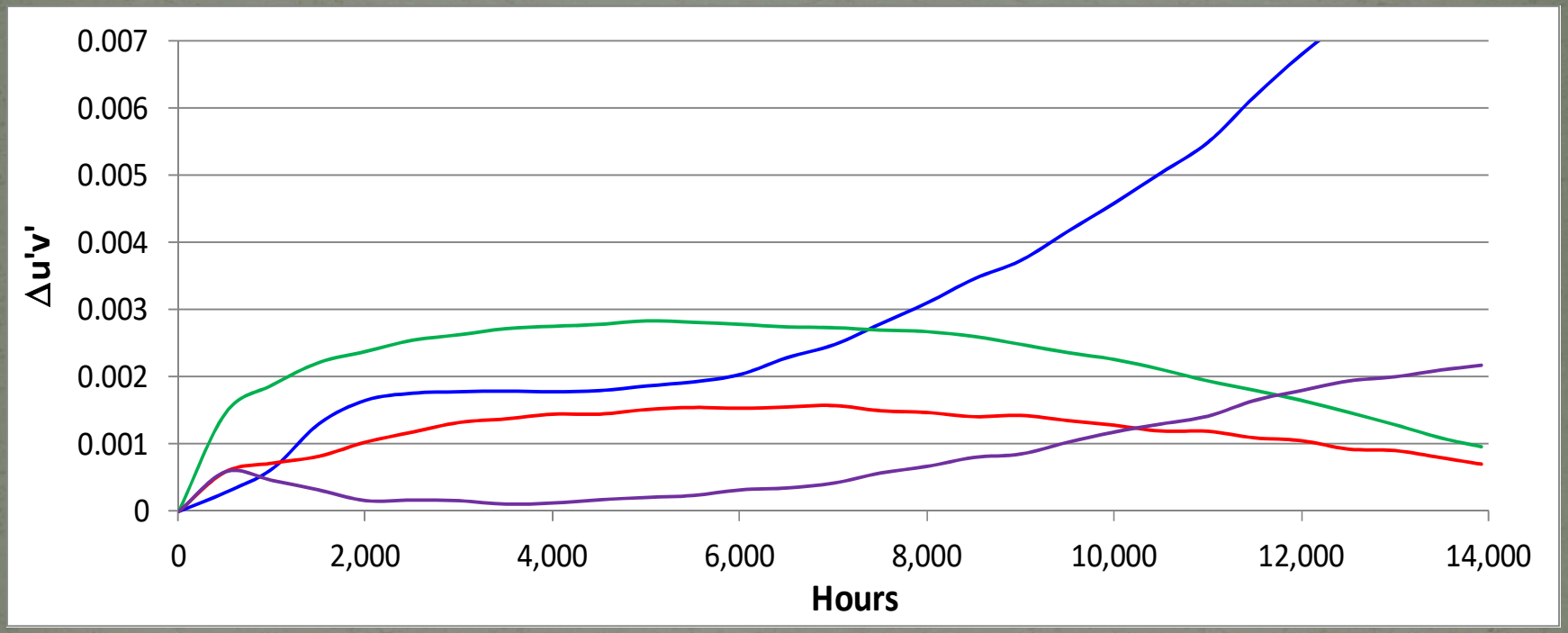
Other Δu'v' Models

- $\Delta u'v'(t) = \Theta(t-d)\cdot a\cdot t^{0.25} + c$
- Requires testing to emergence
- Can not predict decreases in Δu'v'



Wagner et al, Luger Research e.U., issue 59, 34-28 (2017)

Which LED is the Most Stable?

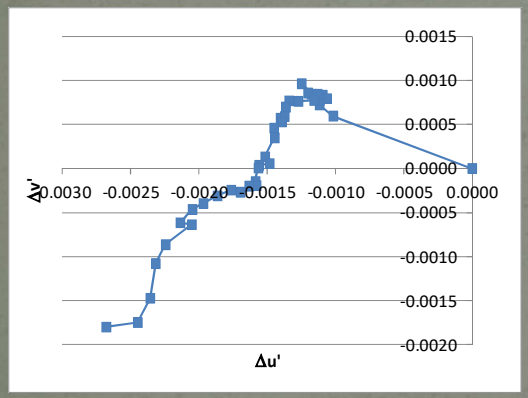


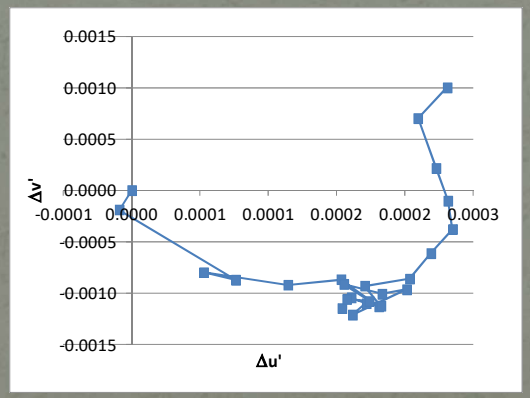
Early behavior does not predict long term trend

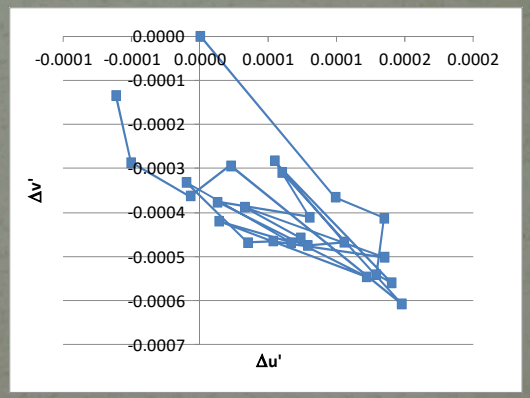
The Color Shift Prediction Challenge

Multiple mechanisms associated with color shift:

- Do we need a model for each mechanism?
- Do we need to know details of package to model?
- CALiPER 20.5 detailed 4 distinct color shift modes
- Color shift behavior can be radically different







Terminology

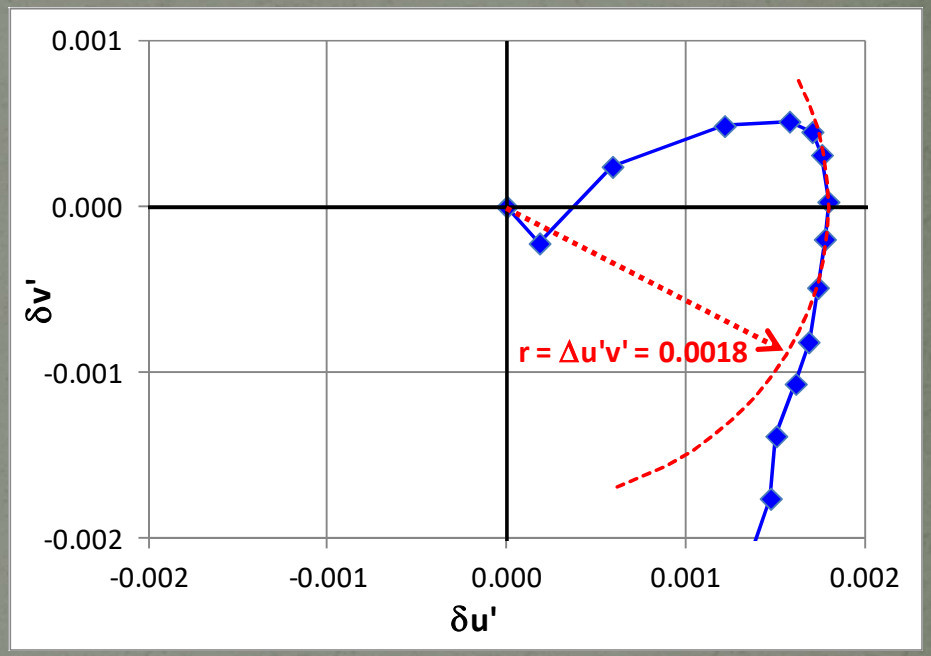
- **Relative chromaticity** ($\delta u', \delta v'$): chromaticity relative to time = 0
- **Incubation period:** period of time during which the chromaticity shift ($\Delta u'v'$) is essentially constant
- **Emergence:** period of time during which chromaticity shift ($\Delta u'v'$) increases monotonically with time
- **CSn:** Time for an LED to exhibit a chromaticity shift ($\Delta u'v'$) of 0.001 x n
  - **CS4 = time to $\Delta u'v'$ = 0.004**
  - **CS7 = time to $\Delta u'v'$ = 0.007**

Going Backwards to Go Forwards

- Chromaticity shift (change in u' and v') is a vector (2-dimensional phenomenon)
- $\Delta u'v'$ is a scalar metric
- During incubation, chromaticity may be changing even if $\Delta u'v'$ is constant
- A successful model must include independent models for u' and v'
- (Strictly) linear models will not accurately capture temporal behavior

The Incubation Artifact

- Strong trend after 3,000 hours
- Du'v' ~constant from 2,000 – 5,000 hours
- Predicting emergence requires new models
- And a new approach



Time Interval = 500 hours

Differential Chromaticity Analysis

- Differential Chromaticity (δ**u**'*, δ**v**'*) is the rate of change in relative chromaticity over a given time interval
  - $\delta u_t'^* = (\delta u'_t - \delta u'_{t-\Delta t})/\Delta t$
  - $\delta v_t'^* = (\delta v'_t - \delta v'_{t-\Delta t})/\Delta t$
- **<u>First Principle:</u>** Differential chromaticity is a linear function of time
- **<u>Second Principle:</u>** Keep all data for $t \geq 2{,}000$ hours

DCA in 5 Easy Steps

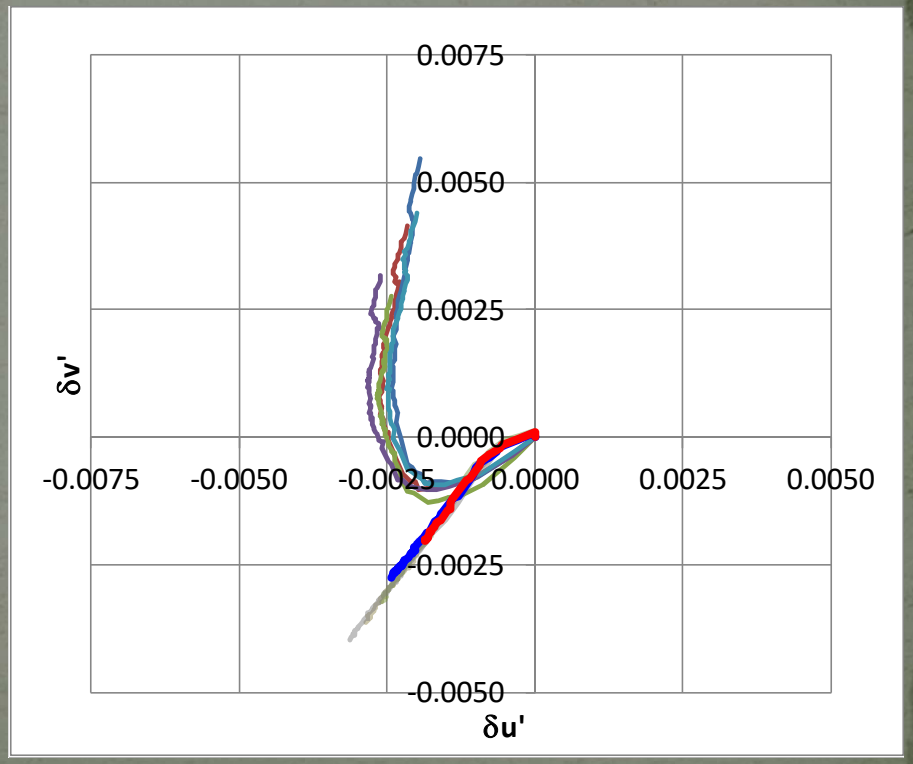
- Convert chromaticity data to relative chromaticity $u', v' \rightarrow \delta u', \delta v'$
- Calculate differential chromaticities $\delta u'^*, \delta v'^*$
- Calculate linear fit of differential chromaticities for $t \geq 2{,}000$ hours
- Use linear fit data to project change rate of chromaticity coordinates
- Calculate future relative chromaticity coordinates

Mathematical Translation

- Calculate relative chromaticities
  - $\delta u'_t = u'_t - u'_o$
  - $\delta v'_t = v'_t - v'_o$
- Calculate differential chromaticities
  - $\delta u_t'^* = (\delta u'_t - \delta u'_{t-\Delta t})/\Delta t$
  - $\delta v_t'^* = (\delta v'_t - \delta v'_{t-\Delta t})/\Delta t$
- Linear fit differential chromaticity data for $t \geq 2{,}000$ hours
  - $\delta u_t'^* = a_{u'}t + b_{u'}$
  - $\delta u_t'^* = a_{v'}t + b_{v'}$
- Project relative chromaticities
  - $\delta u'_{t+\Delta t} = \delta u'_t + \delta u_t'^*\Delta t = \delta u'_t + (a_{u'}t + b_{u'})\Delta t$
  - $\delta v'_{t+\Delta t} = \delta v'_t + \delta v_t'^*\Delta t = \delta v'_t + (a_{v'}t + b_{v'})\Delta t$

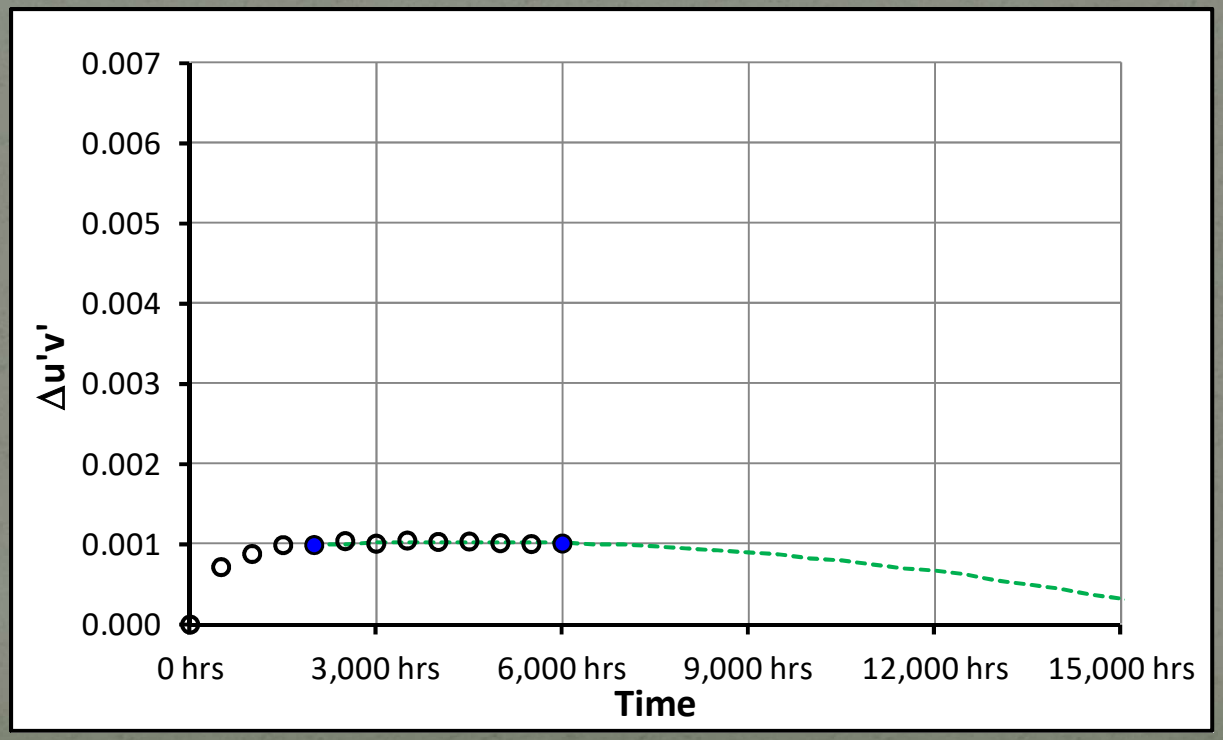
Relative Chromaticity

- Relative chromaticity coordinates shift all LEDs to a common origin
- Simplifies comparisons of different LEDs
- Reducing impact of data drops



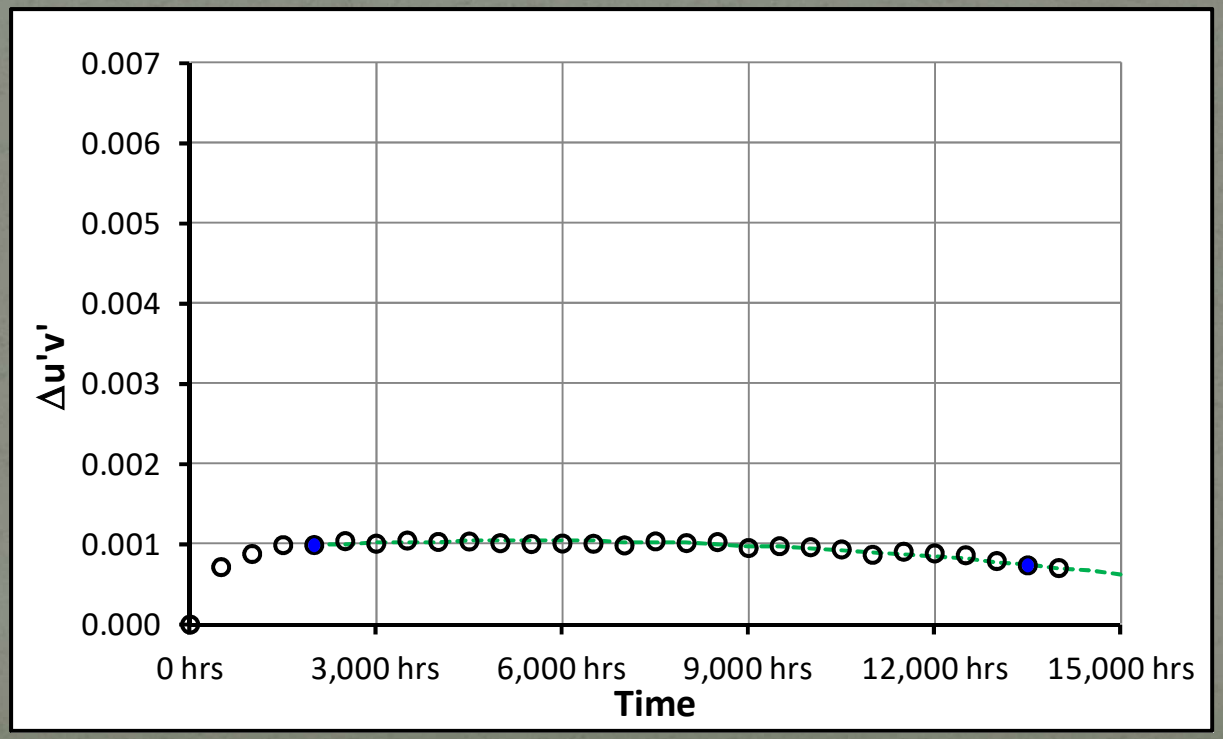
Example 1

- 6,000 hour data shows good stability
- Blue points indicate data analysis window
- DCA model predicts decreasing trend



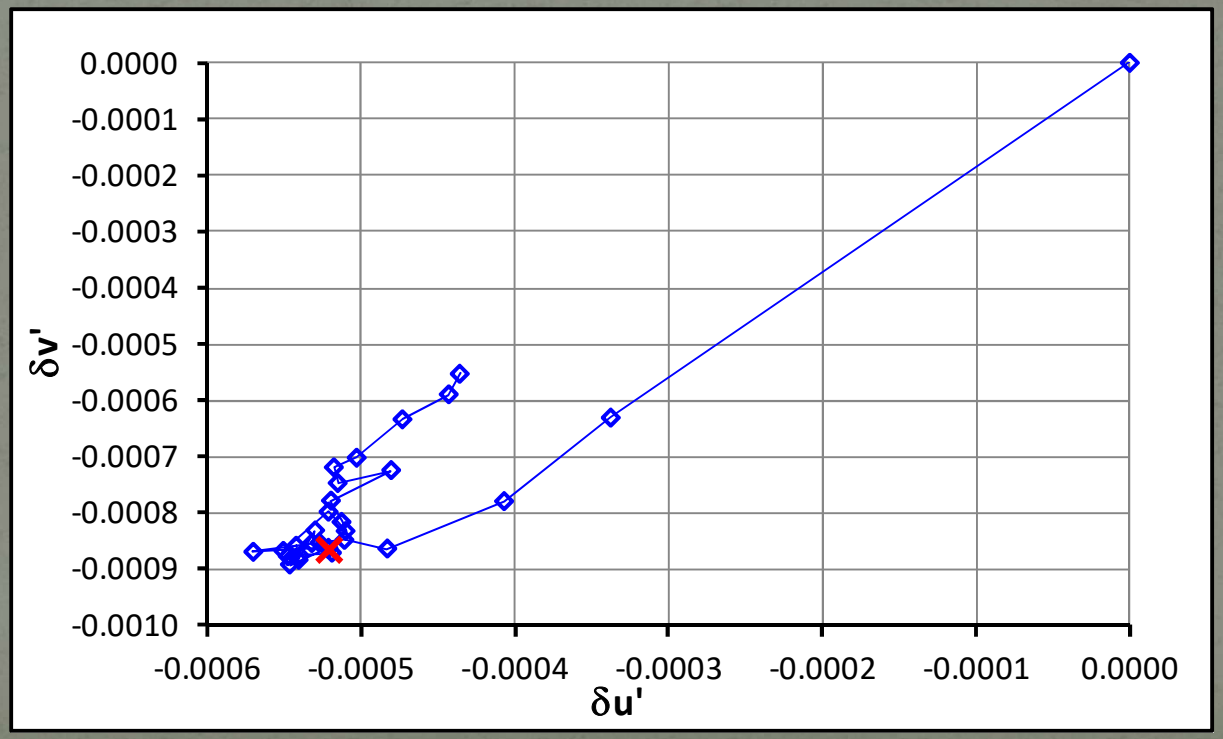
Example 1

- Model closely matches data
- Increasing time interval improves accuracy of prediction with little to no offset over entire data set



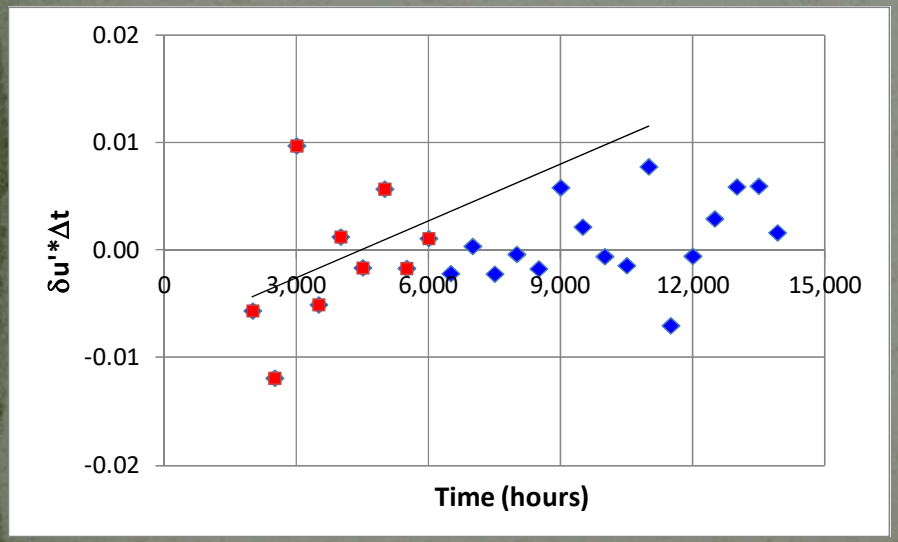
Example 1 – u'v' behavior

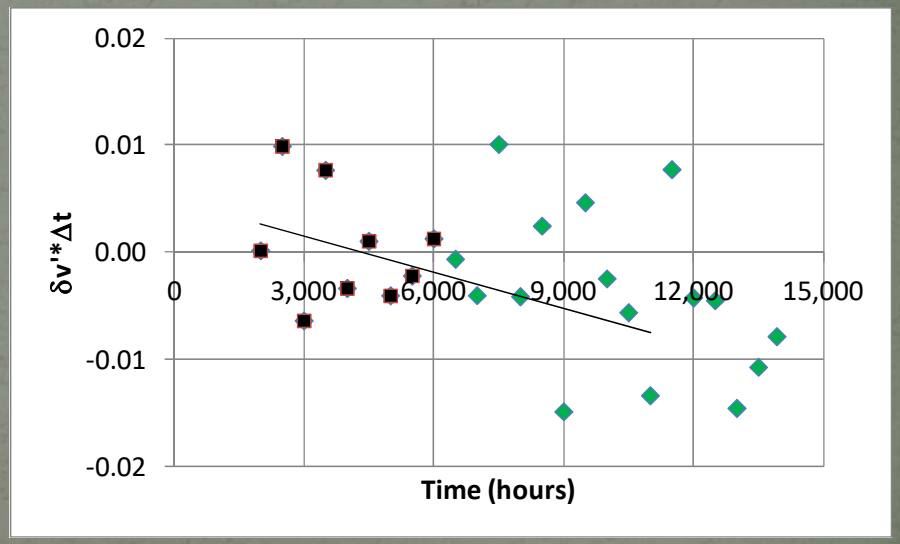
- At 6,000 hours chromaticity shift had virtually ceased
- DCA detected a future reversal



Example 1

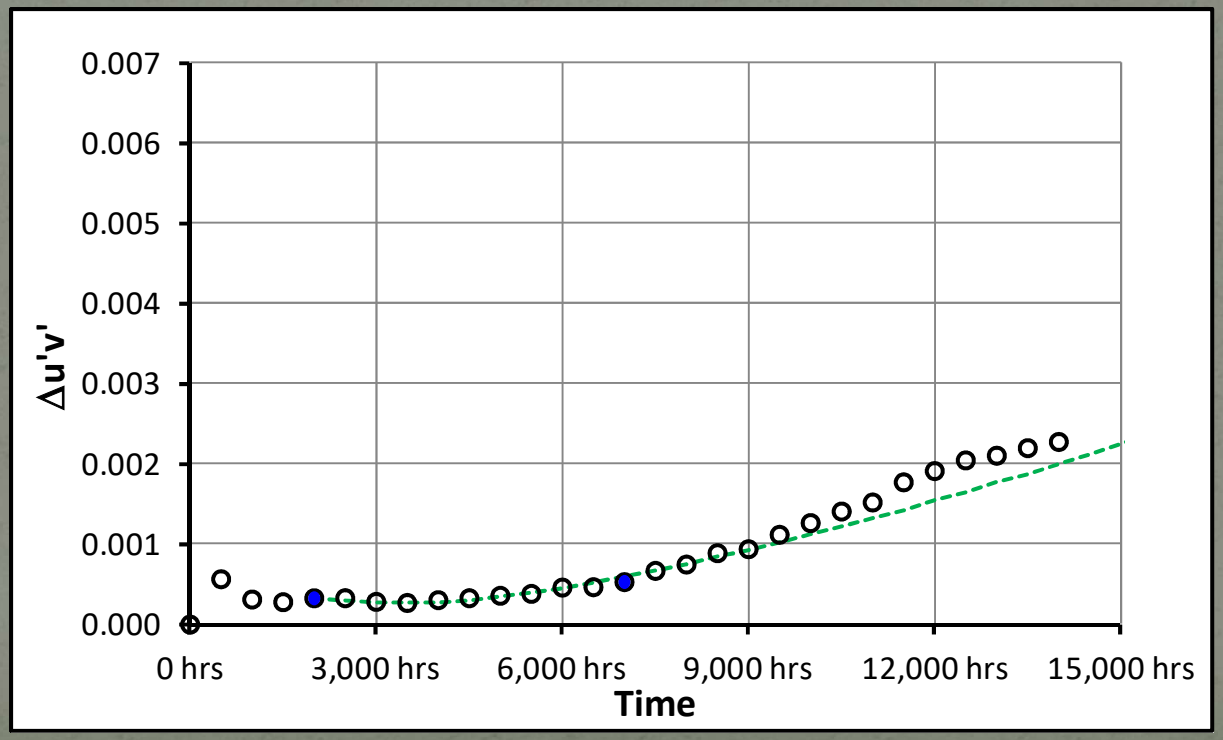
- δu'* & δv'* only approximately linear, but still give excellent results
- Errors in one parameter compensated by errors in the other





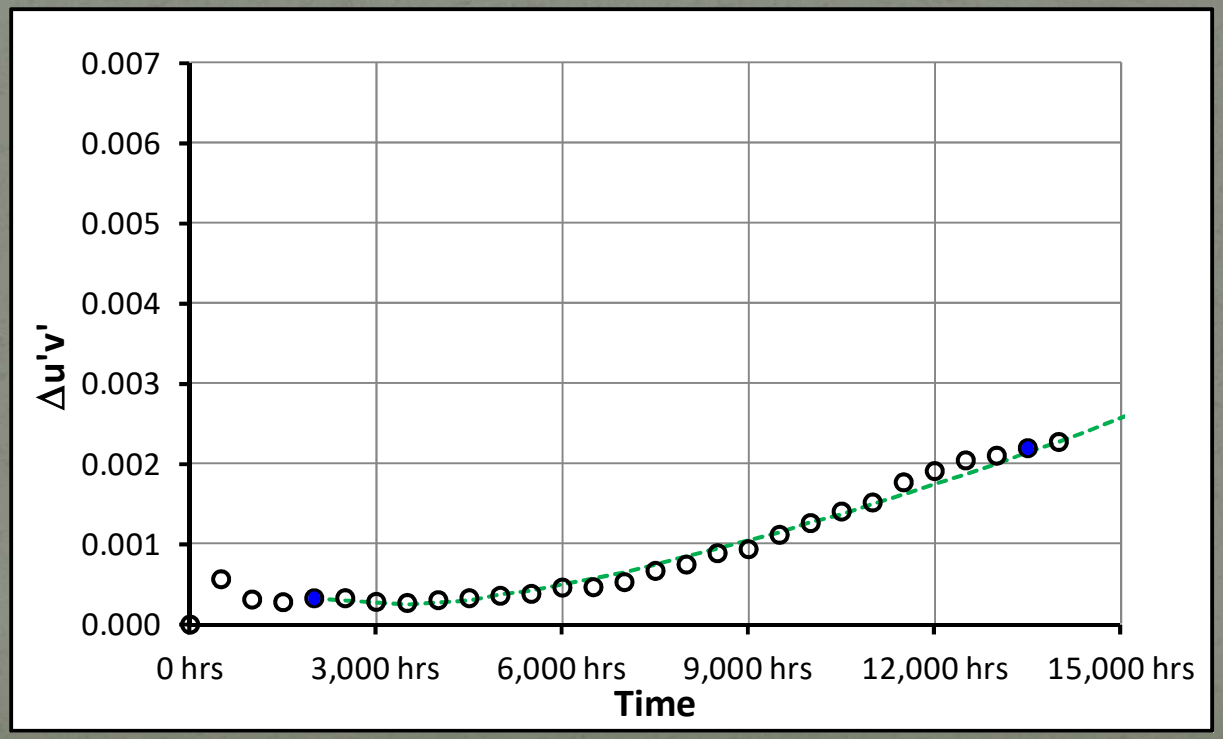
Example 2

- 7,000 hour data shows exceptional stability
- DCA model predicts decreasing trend
- Trend matches future behavior



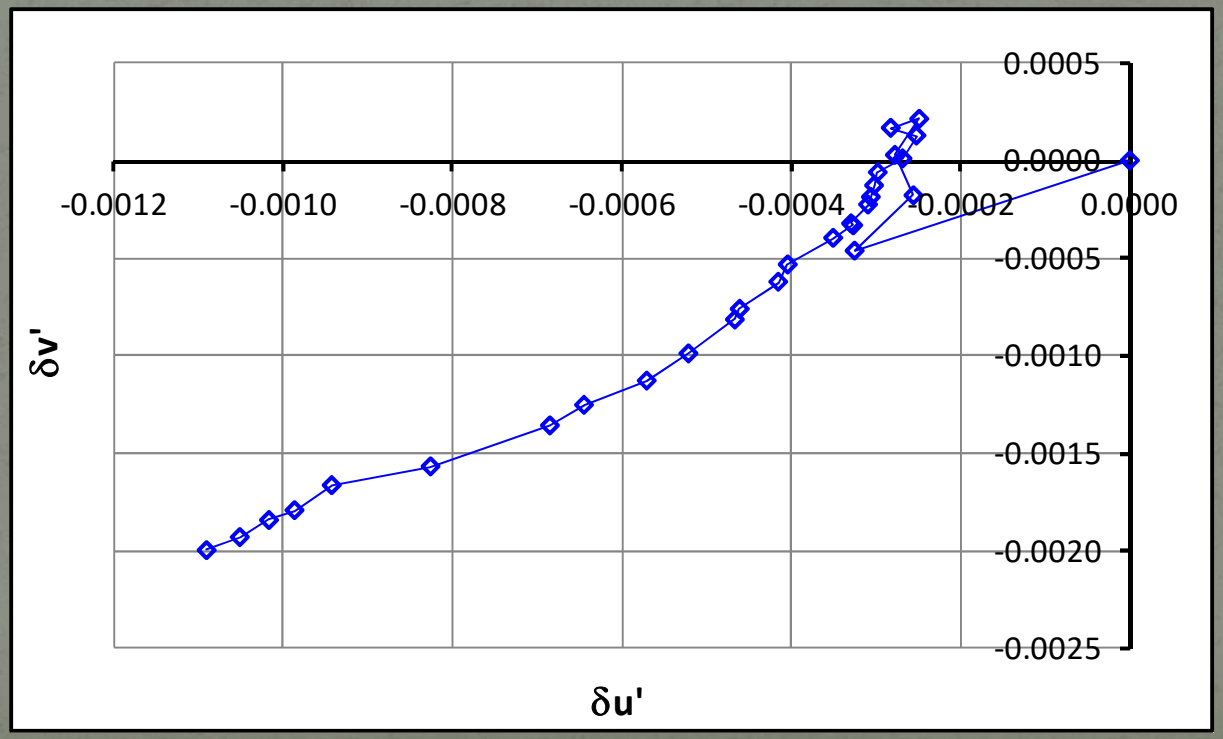
Example 2

- DCA model again provides close fit to the entire data set



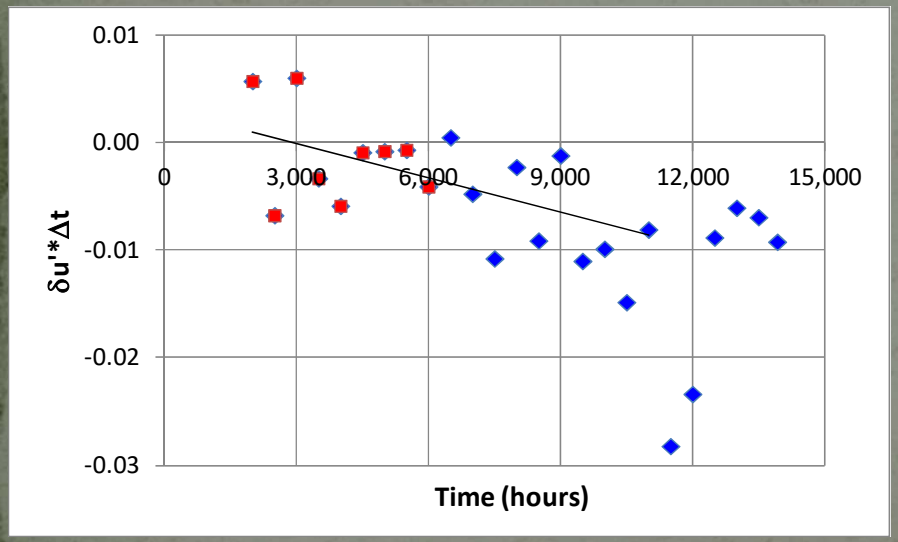
Example 2 – u'v' behavior

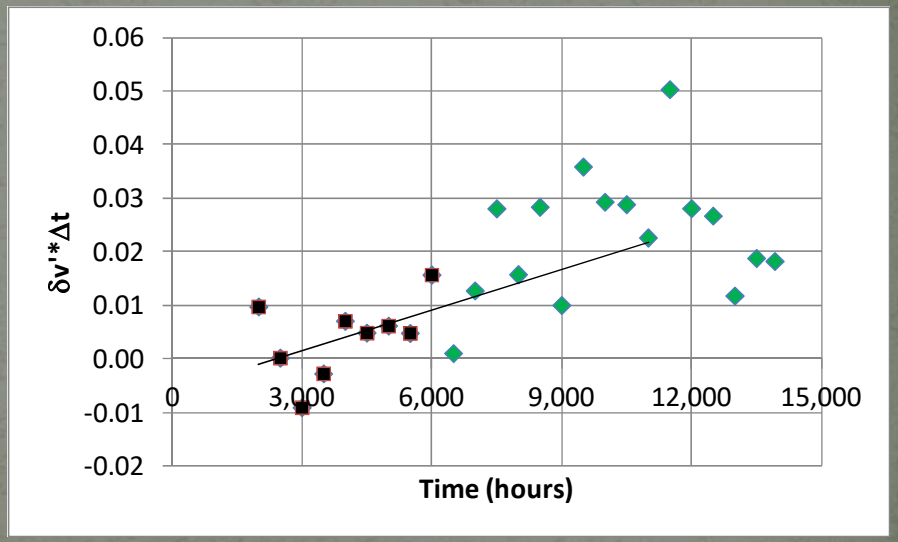
- Modeled data included ~ 180° direction change in chromaticity shift behavior



Example 2

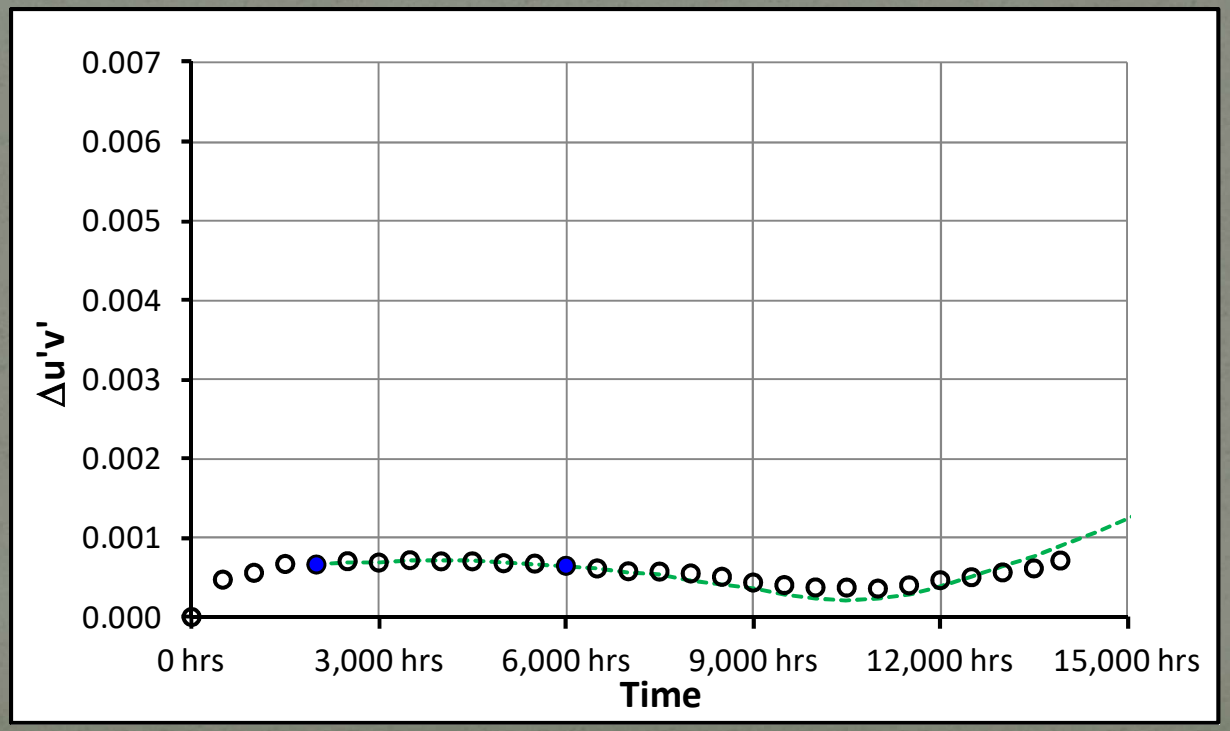
- δu'* & δv'* only approximately linear, but still give excellent results
- Errors in one parameter compensated by errors in the other





Example 3

- Δu'v' ~constant up to 6,000 hours
- DCA model predicts decrease followed by emergence
- Prediction matches data



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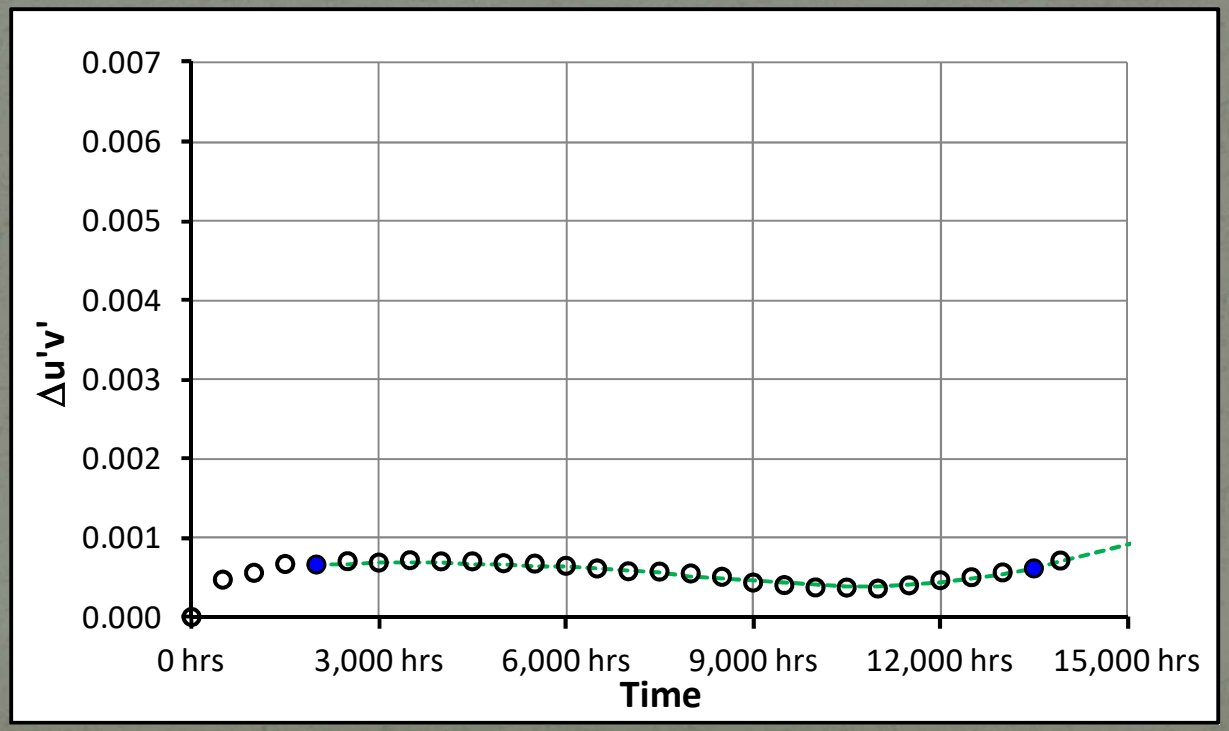
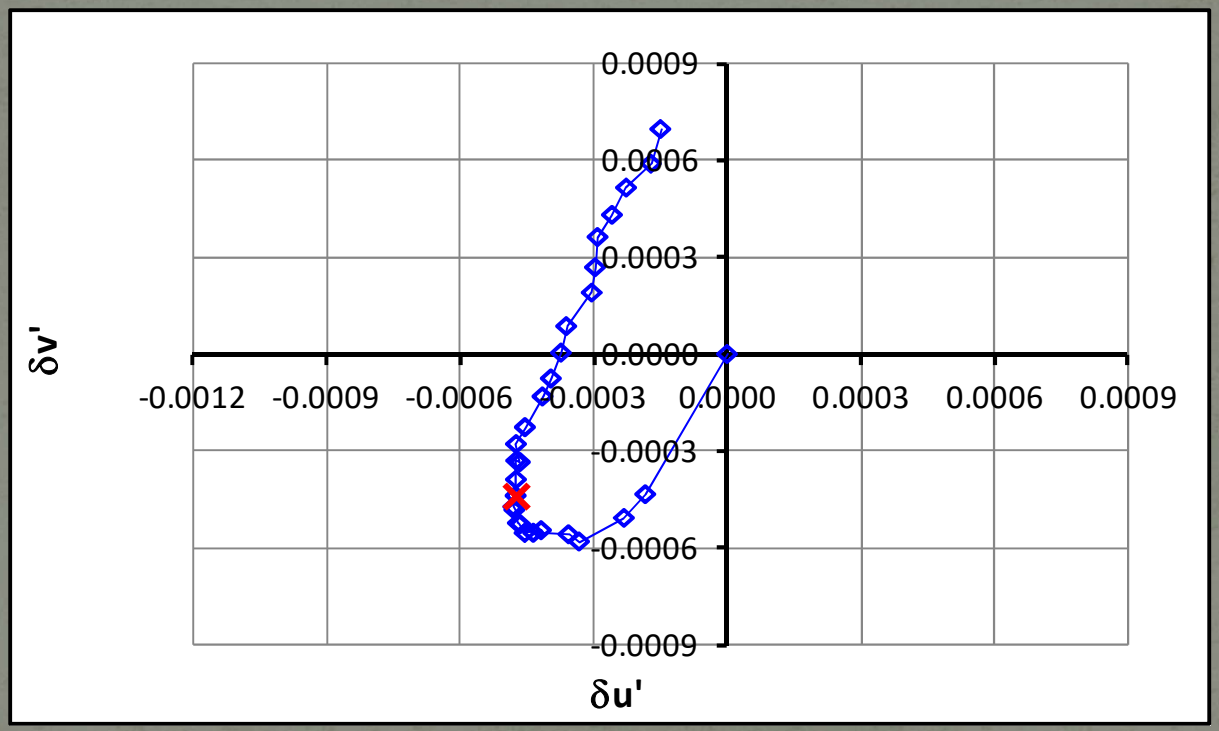


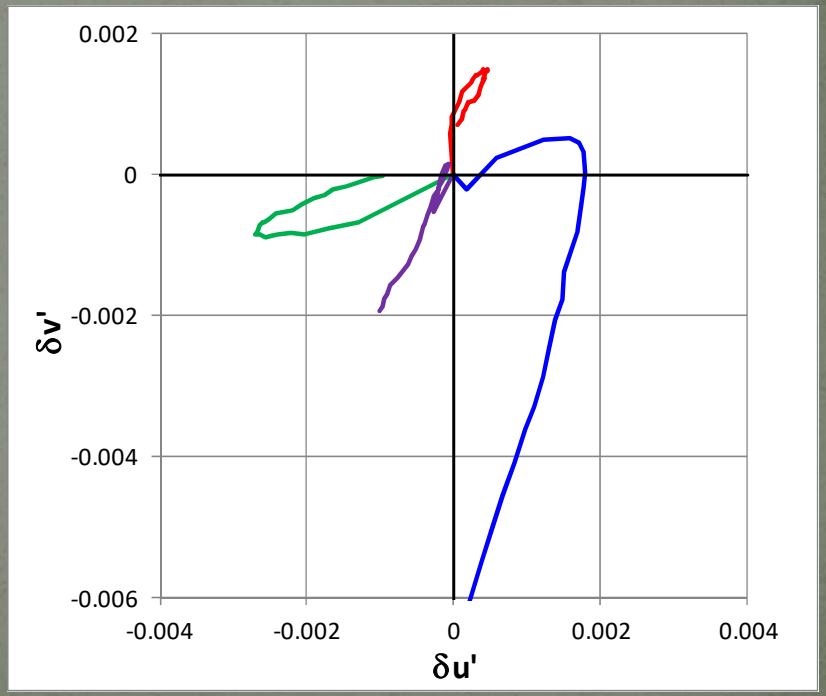
Example 3 – u'v' behavior

- Long term trend predicted before firmly established



Model Validation

- IES TM-31 work group has tested model against >200 data sets
- DCA can successfully model a wide range of chromaticity shift behaviors
- Differential parameters allow ***prediction*** of changes in shift direction

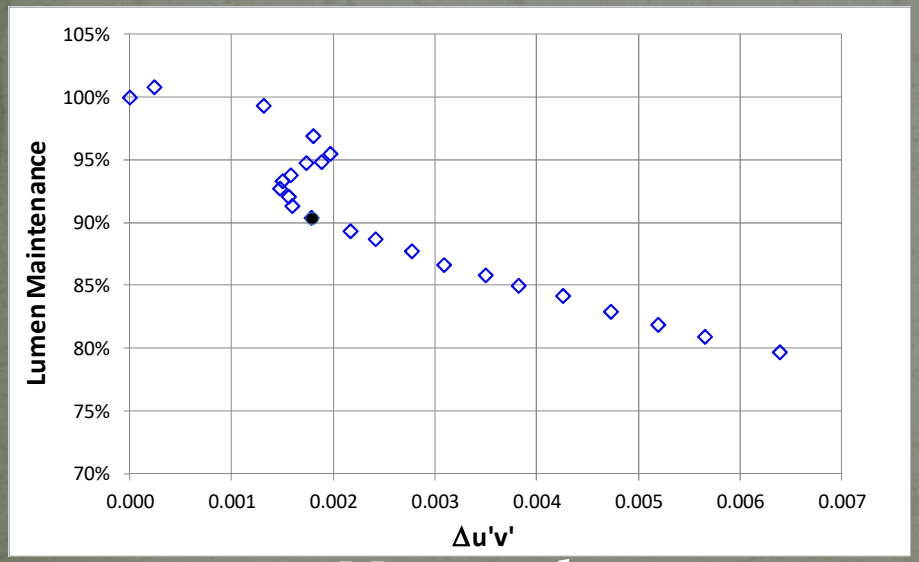


DCA Comments

- Package type and material agnostic
- Powerful predictive capabilities – can predict emergence
- Able to accurately model large time spans of complicated data
- Inherently unstable model – it will always give finite values for CS7; estimates converge as more data is included in the analysis
- Advanced versions of model chromaticity behavior that stabilizes

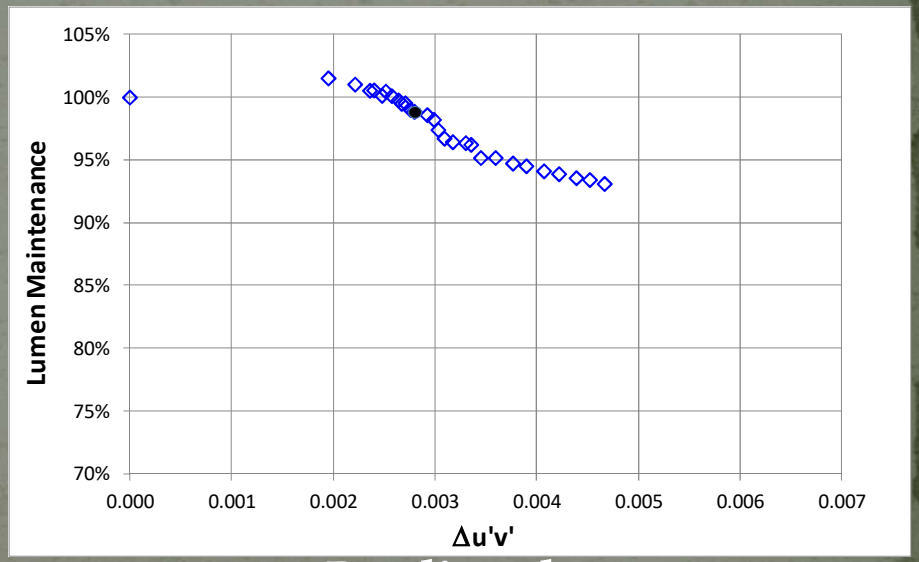
Showing Data

- LED output may fail for lumen maintenance or chromaticity shift
- Plotting data on same graph illustrates why we should be very concerned about chromaticity shifts



Measured

CS7 = 12,100 hrs, LM = 78.5%



Predicted

CS7 = 21,270 hrs, LM = 87.5%

Acknowledgements

- PNNL
- Ralph Tuttle
- Lynn Davis

Thank you

Questions????