VALIDATION OF COMPUTATIONAL ELECTROMAGNETICS

Alistair Duffy

IN THE BEGINNING GOD SAID:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

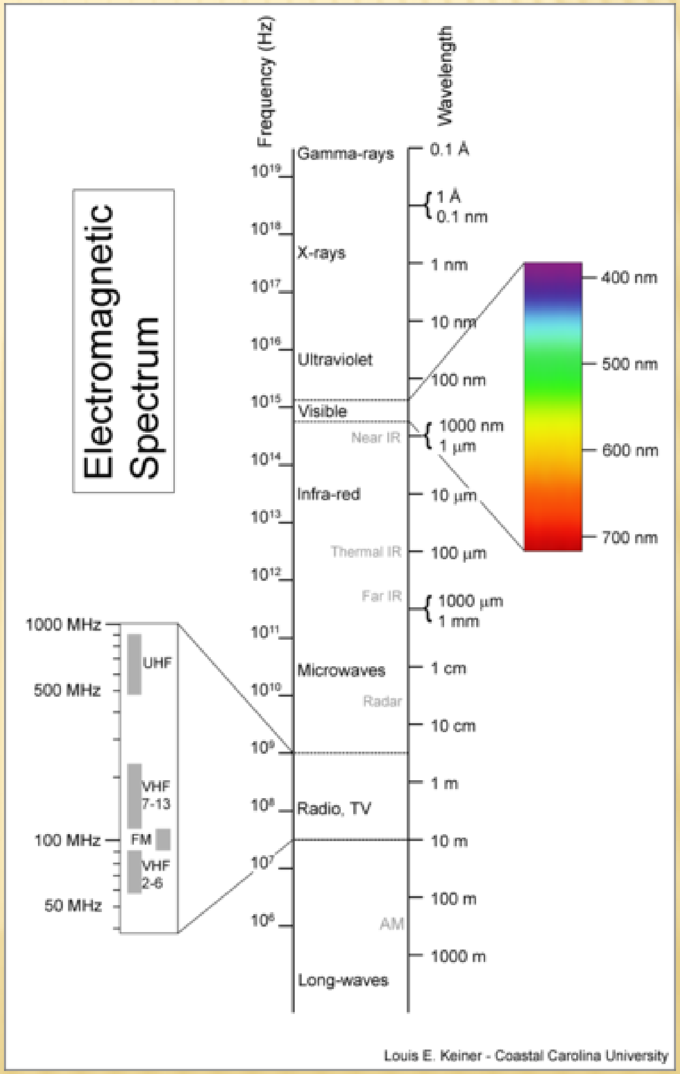
$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

$$\nabla \bullet \mathbf{B} = 0$$

$$\nabla \bullet \mathrm{D} = \rho$$

AND THERE WAS LIGHT

- And all manner of other electromagnetic radiation.



MAXWELL'S EQUATIONS

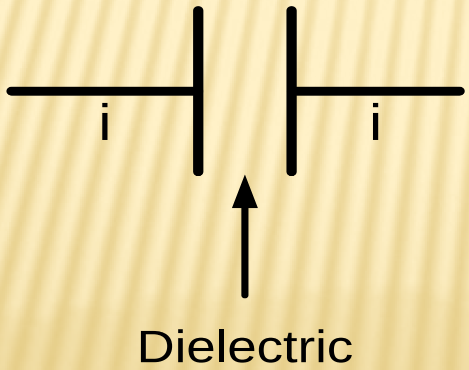
- These four innocuous looking equations hide some dark secrets:
  - The pain and suffering they have caused many a student and practicing engineer.
  - The, almost naughty, pleasure they have caused others.
- In all cases the solution to any non-trivial problem becomes unmanageable very quickly.

A BIT TRICKY

- For those of you who know them, you probably don’t need to be reminded.
- For those of you who don’t know them, you may need more than the next hour in order to enjoy their full beauty.

USEFUL CONCEPTS

- They are needed even in basic electronics to answer such questions as “if Kirchhoff’s current law is correct, how come a capacitor works?”



$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

ENOUGH OF PARTY TRICKS

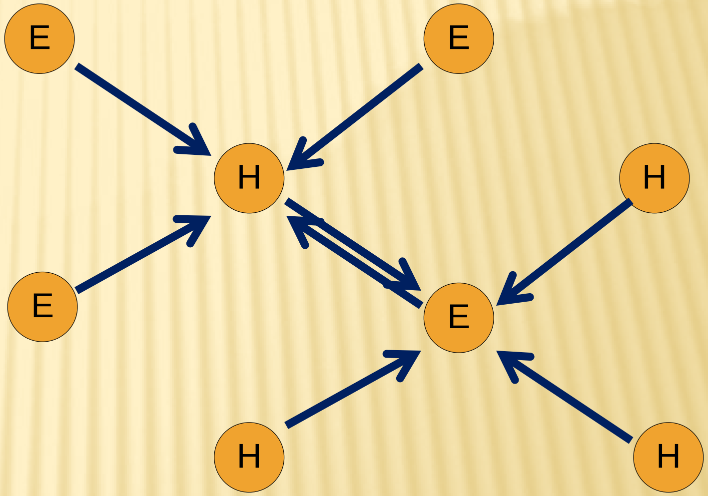
- We want to be able to use this knowledge to do more than electromagnetic theory parlour tricks. We want to:
  - Design antennas.
  - Make sure electronic equipment works in the presence of other electronic equipment.
  - Calculate how much power is dissipated in a human brain when using a mobile phone.
  - Design RF MEMS

WHAT'S THE BEST WAY TO EAT AN ELEPHANT?

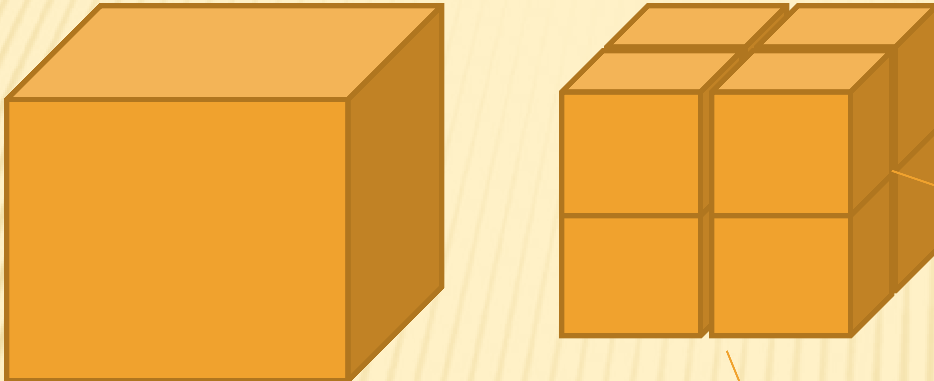
- A bite at a time
- Rather than trying to derive an equation that expresses the currents on a wire in a complex cavity, it is usual to model the system where the model is made up of small elements, where Maxwell's equations can be applied with confidence.
- A couple of examples of this are the Finite Difference Time Domain technique and the Transmission Line Matrix method.

FINITE DIFFERENCE TIME DOMAIN

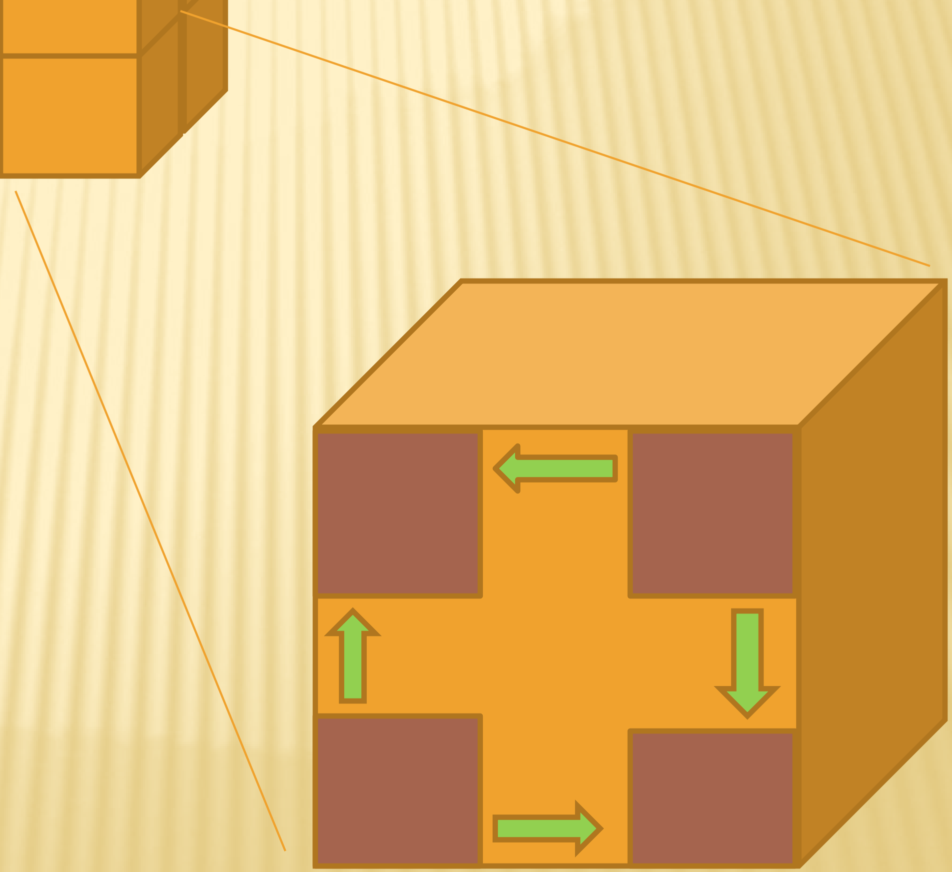
- A leapfrog matrix of points at which E and H fields are known is created and a difference scheme is used to calculate the H fields due to the E fields around them and then the E fields due to the H fields and then the E fields due to the H fields again, etc. until an acceptable level of stability or resolution is achieved.



TRANSMISSION LINE MATRIX METHOD



Becomes



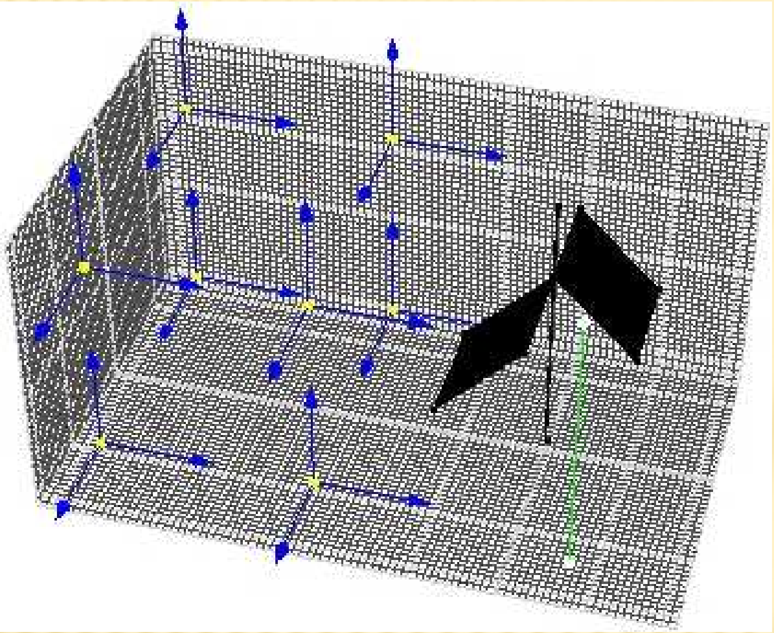
The duality between E & H fields and voltage and current is exploited by treating space like a network of intersecting transmission lines

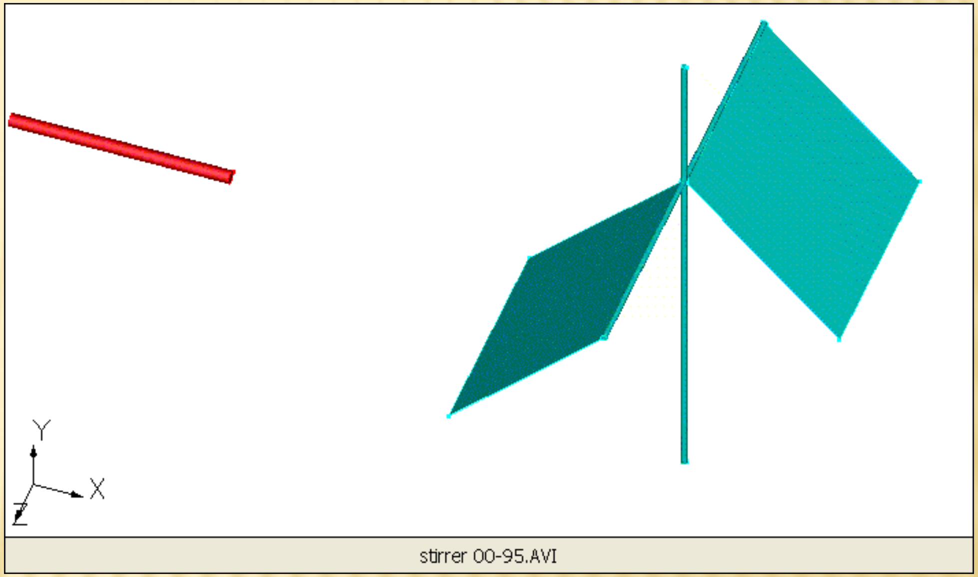
EXAMPLE – REVERBERATION CHAMBER

- ‘Faraday cage’ with rotating mechanical stirrer to mix the modes internally.
- Isolates internal and external environments
- Exposes equipment to potentially high field strengths
- Almost (if not actually) impossible to solve E(x,y,z,f,t) analytically. (We used TLM to get current on a wire in the chamber)

ACTUAL:

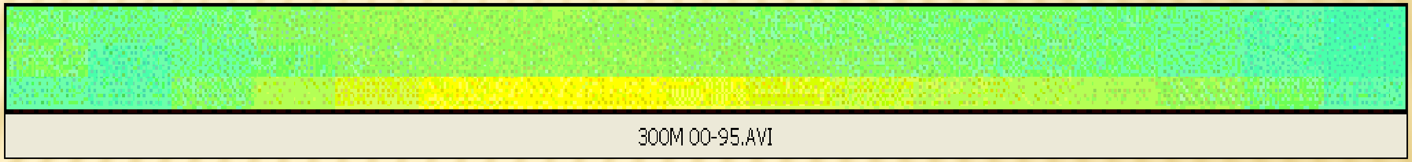
MODEL





RESULTS

- Current on the surface of the wire (think of trying to solve Maxwell's equations for *J*)



THAT'S ALL VERY WELL AND GOOD BUT…

- Pretty pictures are good. They help to develop an understanding of the performance of the system.
- They mean nothing, though, unless they bear a recognisable similarity to the real world.
- Models need to include enough detail and measurements need to exclude unnecessary detail – where possible.

A WORD OF WARNING

- It should be noted that models are based on simplified, often idealised, views of the world.
- Real measurements often include confounding variables (such as cable placement)
- The idea of being able to model a complex system, measure it and get a 1:1 agreement is naïve.
- What we need to decide is when a model (or measurement) is good enough.

HISTORICALLY…

- The comparisons have been 'eye-balled' and decisions made by experienced engineers. However,
  - There will be a range of opinions
  - Binary decisions are difficult to make
  - Any 'knowledge technology' must be seen to be in agreement with human decisions.

OH DEAR!

- This means we need to be able to define ‘good enough’. This is not easy.
- Ok, which one of these is bluer?

OR

Is it better to open an egg at the big end or the little end?

ACTUAL OPINION IS …

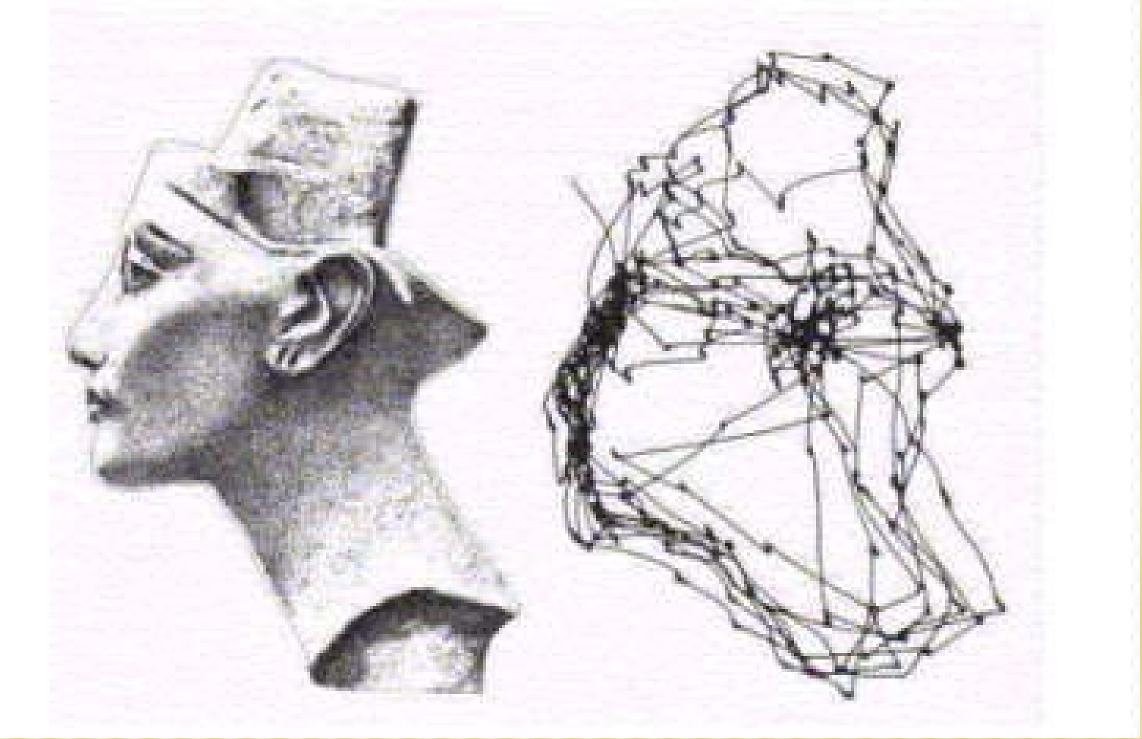
- Personal and individual
- A general level of agreement between individuals can be expected but each person being asked for an opinion will have a different background and, as we are the sum of our previous experiences, we could not expect everyone to agree.

HOWEVER, STATISTICS…

- Is like a bikini. What it reveals is enticing and what it hides is vital.
- Doesn’t help at a general level. In some circumstances correlation or non-parametric statistics could be used, but often, the same value can be derived from a number of different comparisons.
- What we need is a way of helping the decision making process.

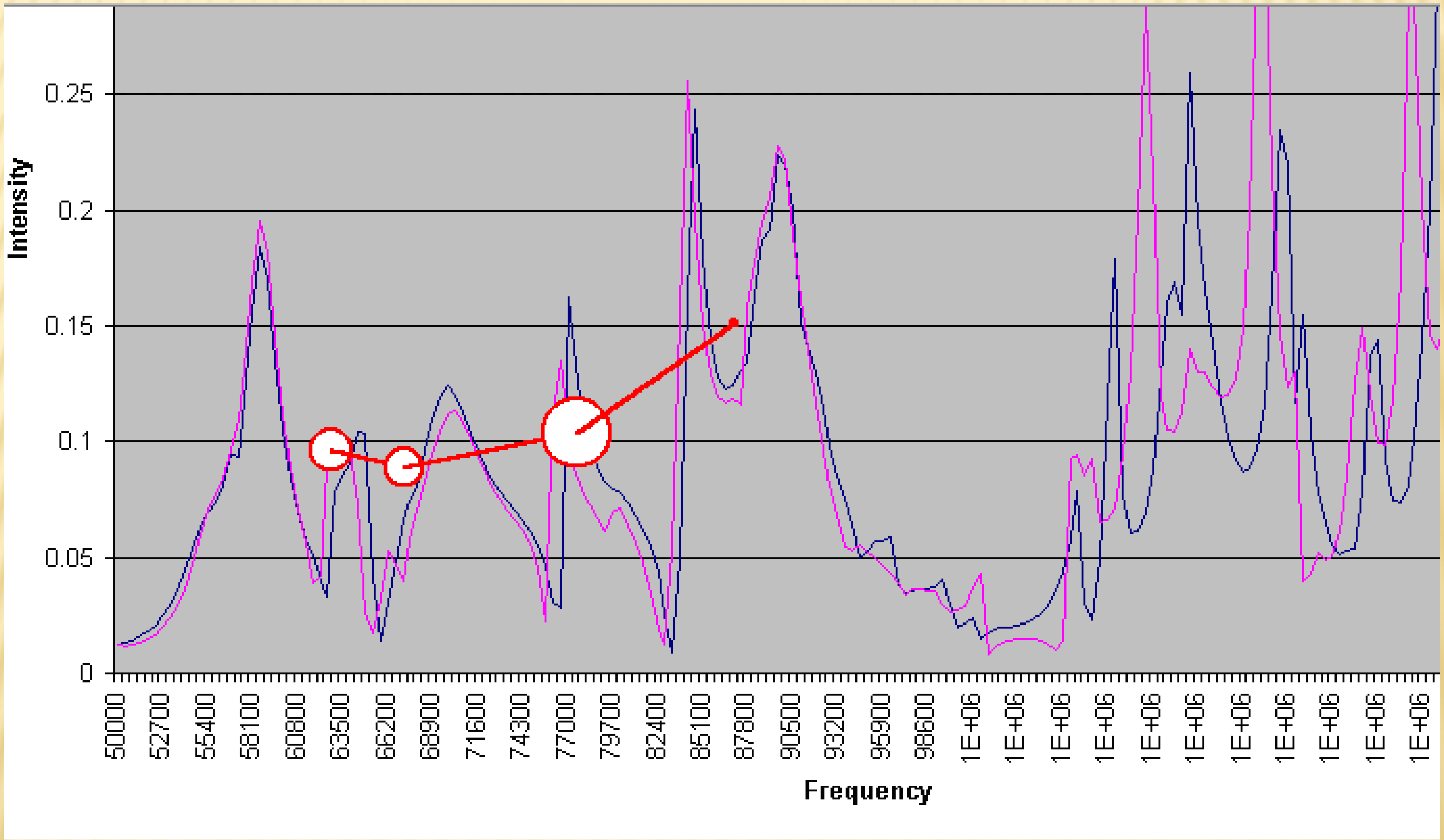
WHAT DO PEOPLE LOOK AT?

- The bust of Queen Nefertiti:

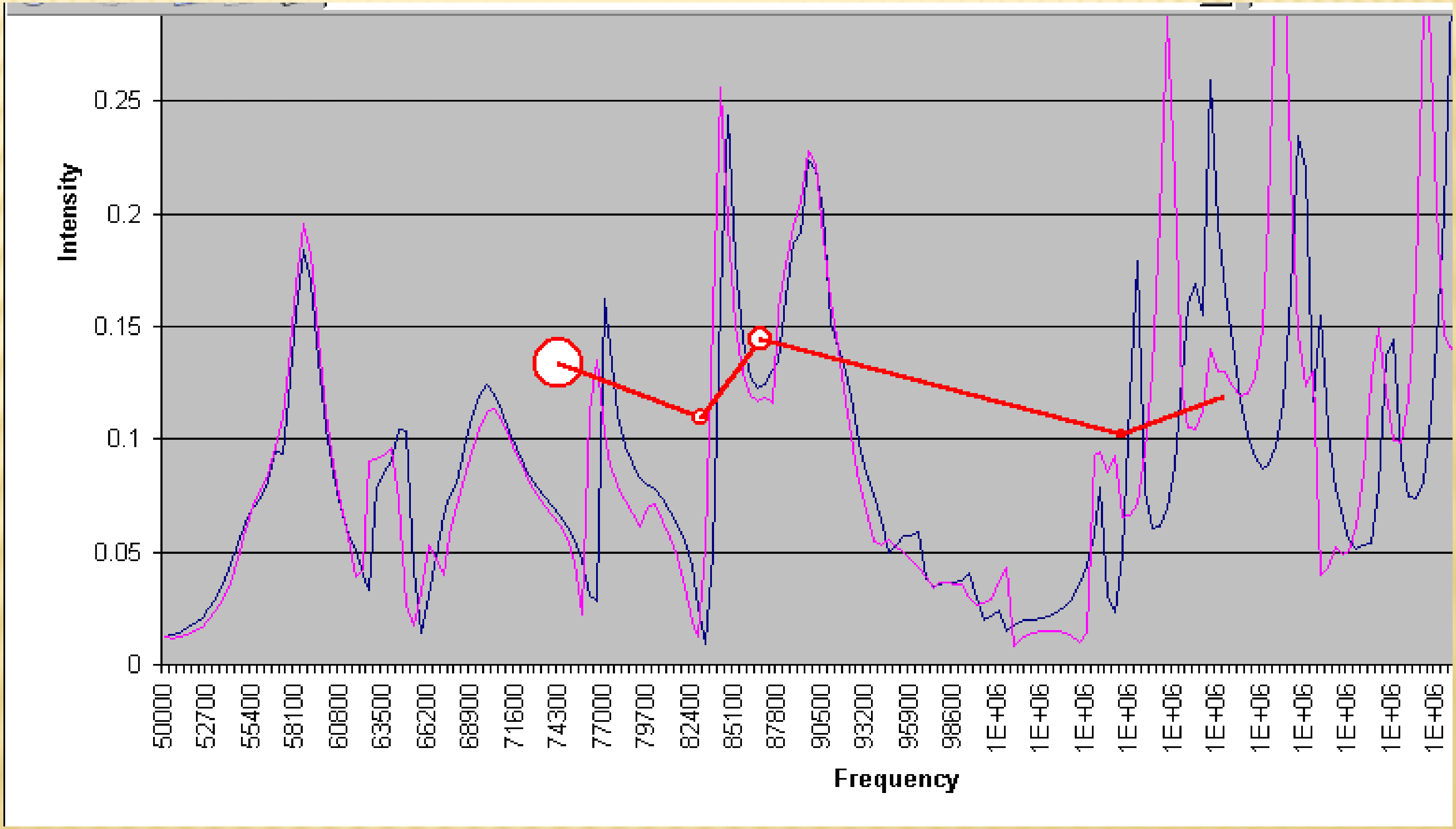


- Shapes and fine detail.

OR, IN A MORE FAMILIAR DOMAIN TO US



AND



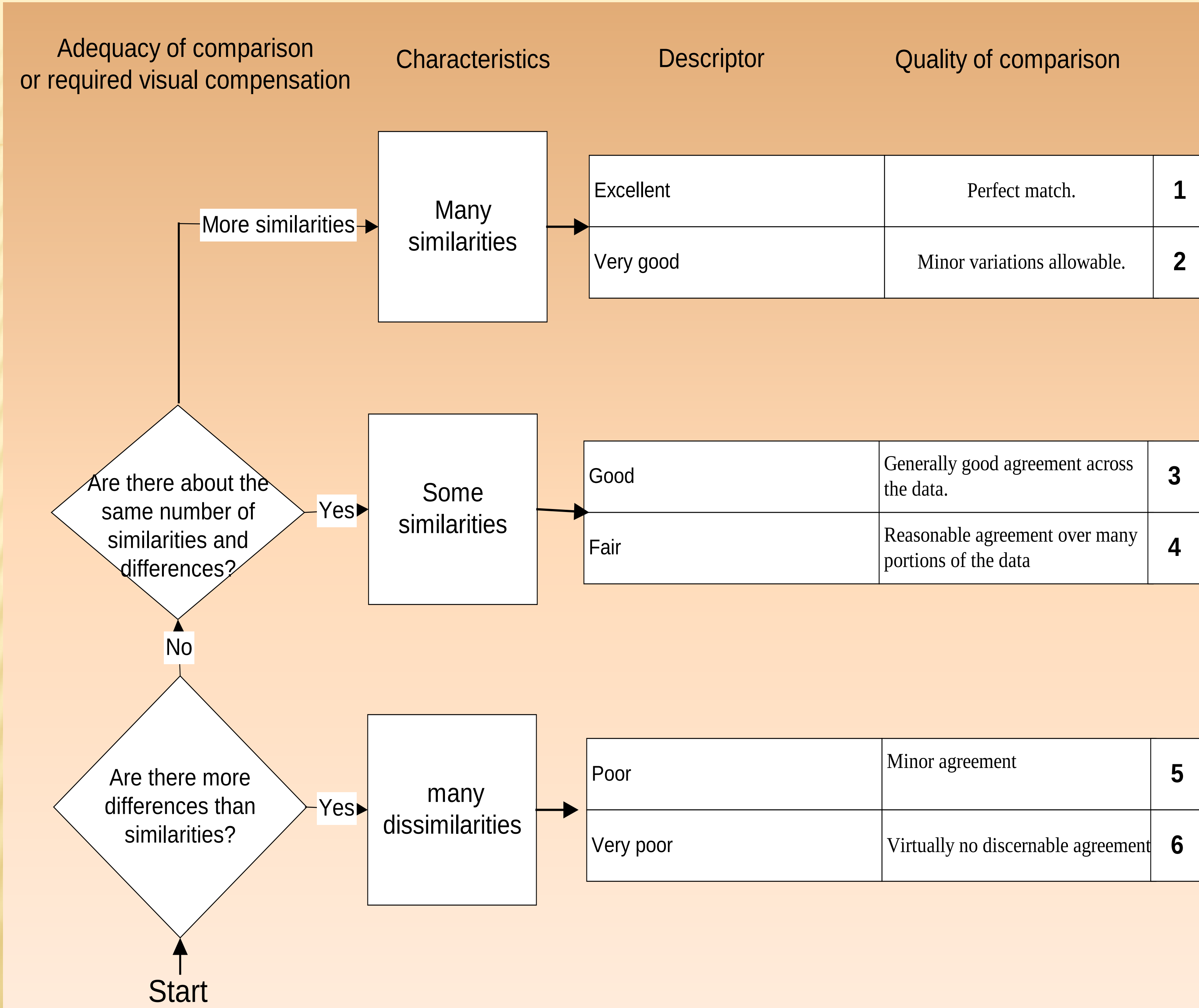
Intensity
0.25
0.2
0.15
0.1
0.05
0
50000
52700
55400
58100
60800
63500
66200
68900
71600
74300
77000
79700
82400
85100
87800
90500
93200
95900
98600
1E+06
Frequency

TAKING THE NEXT STEP

- We are looking for a range of opinions and need to accept that a binary decision is difficult
- People like to categorise and use natural language descriptions.
- There is no *a priori* definition of ‘good’, ‘bad’ or anything in between.
- Before being able to be confident about any computer based method we need to be able to capture this opinion.

VISUAL RATING SCALE

- 1 – 10 scales are artificial and unusable.
- Likert scales mean making one five option decision.
- Our visual rating scale provides a ‘fuzzy’ decision based on a set of binary decisions.


Adequacy of comparison or required visual compensation
Characteristics
Descriptor
Quality of comparison
More similarities
Many similarities
Excellent
Perfect match.
1
Very good
Minor variations allowable.
2
Are there about the same number of similarities and differences?
Yes
Some similarities
Good
Generally good agreement across the data.
3
Fair
Reasonable agreement over many portions of the data
4
No
Are there more differences than similarities?
Yes
many dissimilarities
Poor
Minor agreement
5
Very poor
Virtually no discernable agreement
6
Start

WHAT ENGINEERS NEED

- A validation tool must be able to:
  - Provide a numerical output that helps quantify a comparison in a way that they would interpret it themselves.
  - Ideally provide a range of ‘support’ to help understand the causes of good or poor comparison (not really discussed in this talk so far)
  - Use natural language descriptors so that the output has a bearing on ‘real life’

THE FEATURE SELECTIVE VALIDATION METHOD

- Breaks down the data to be compared into trend/envelope data and high-Q feature data.
- This seems to mirror the two general areas that engineers look at, namely the shapes and the features.
- Initially developed by Dr Anthony Martin during his PhD studies with me.

SOME VALIDATION DESIGN PRINCIPLES

1. Implementation of the validation technique should be simple
2. The technique should be computationally straightforward
3. The technique should mirror human perceptions and be largely intuitive
4. The method should not be limited to data from a single application area
5. The technique should provide tiered diagnostic information
6. The comparison should be commutative.

SOME TERMINOLOGY

- GDM = global difference measure
- ADM = amplitude difference measure
- FDM = feature difference measure

$$GDM(f) = \sqrt{ADM(f)^2 + FDM(f)^2}$$

OUTLINE OF THE FSV METHOD

The following is a very short description of the FSV method.

1. After taking the overlapping portion of the two data sets and interpolating them, if necessary, so that they have coincident x-axis locations, the data is Fourier Transformed.
2. Both data sets are low-, band- and high- pass filtered. The low pass gives offset information (aka DC), the band-pass gives trend information (aka Lo), the high-pass gives the feature information (aka Hi).

A BIT MORE…

3. These six elements (DC, Lo and Hi for the two data sets) are inverse transformed.
4. The Amplitude Difference Measure (ADM) and Feature Difference Measure (FDM) are constructed according to the following slides

WARNING

ALGEBRA ALERT

ADM

$$ADM(f)=\left|\frac{\alpha}{\beta}\right|+\left|\frac{\chi}{\delta}\right|e^{\left|\frac{\chi}{\delta}\right|}$$

$$\alpha=\left(\left|\mathrm{Lo}_1(n)\right|-\left|\mathrm{Lo}_2(n)\right|\right)$$

$$\beta=\frac{1}{N}\sum_{i=1}^{N}\left[\left(\left|\mathrm{Lo}_1(i)\right|+\left|\mathrm{Lo}_2(i)\right|\right)\right]$$

$$\chi=\left(\left|\mathrm{DC}_1(n)\right|-\left|\mathrm{DC}_2(n)\right|\right)$$

$$\delta=\frac{1}{N}\sum_{i=1}^{N}\left[\left(\left|\mathrm{DC}_1(i)\right|+\left|\mathrm{DC}_2(i)\right|\right)\right]$$

FDM

$$FDM(f) = 2\left(\left|FDM_1(f) + FDM_2(f) + FDM_3(f)\right|\right)$$

$$FDM_1(f) = \frac{\left|\mathrm{Lo}_1{}'(f)\right| - \left|\mathrm{Lo}_2{}'(f)\right|}{\frac{2}{N}\sum_{i=1}^{N}\left[\left(\left|\mathrm{Lo}_1{}'(i)\right| + \left|\mathrm{Lo}_2{}'(i)\right|\right)\right]}$$

$$FDM_2(f) = \frac{\left|\mathrm{Hi}_1{}'(f)\right| - \left|\mathrm{Hi}_2{}'(f)\right|}{\frac{6}{N}\sum_{i=1}^{N}\left[\left(\left|\mathrm{Hi}_1{}'(i)\right| + \left|\mathrm{Hi}_2{}'(i)\right|\right)\right]}$$

$$FDM_3(f) = \frac{\left|\mathrm{Hi}_1{}''(f)\right| - \left|\mathrm{Hi}_2{}''(f)\right|}{\frac{7.2}{N}\sum_{i=1}^{N}\left[\left(\left|\mathrm{Hi}_1{}''(i)\right| + \left|\mathrm{Hi}_2{}''(i)\right|\right)\right]}$$

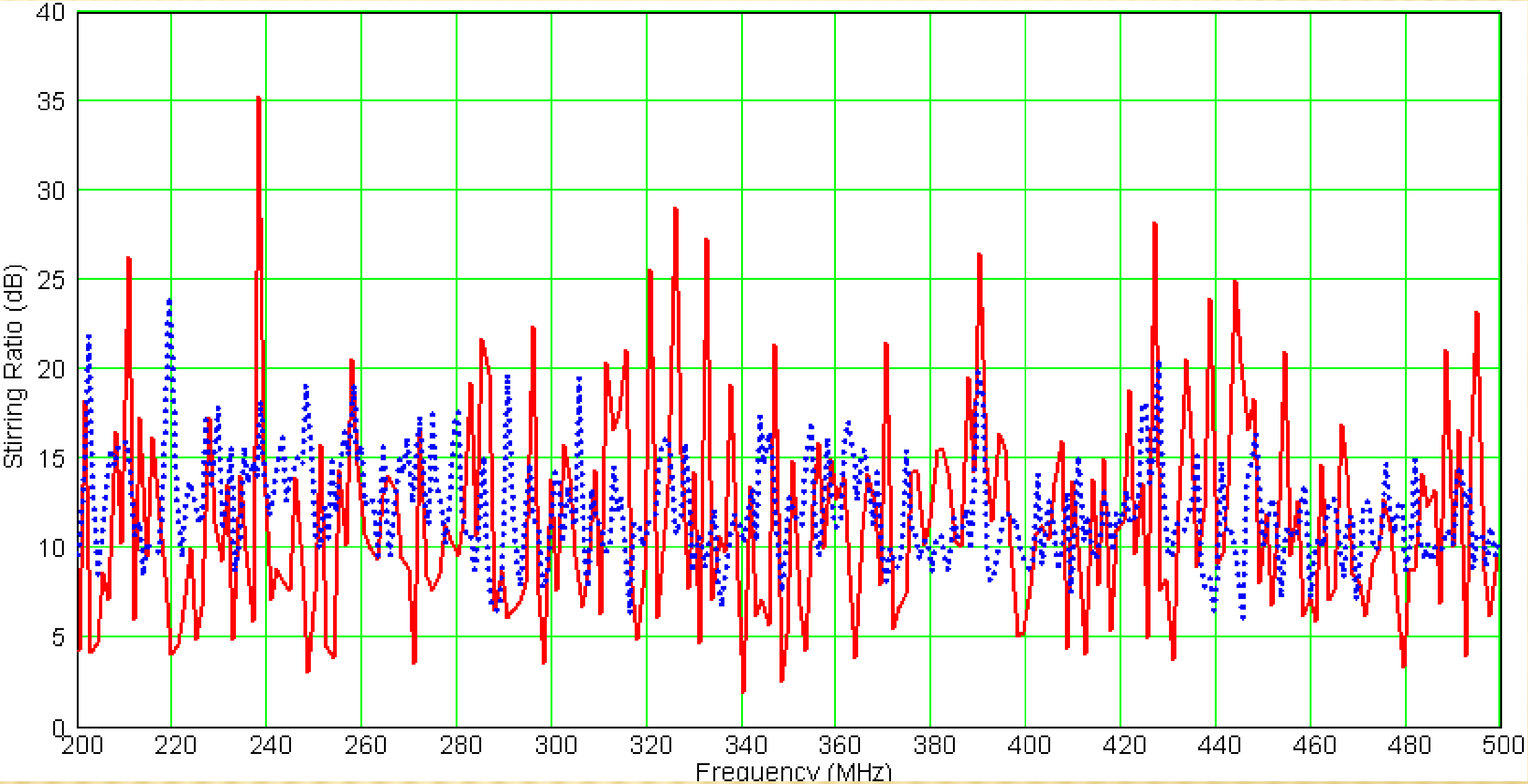
IN RELATION TO NATURAL LANGUAGE

FSV value (quantitative)	**FSV interpretation (qualitative)**
Less than 0.1	Excellent
Between 0.1 and 0.2	Very good
Between 0.2 and 0.4	Good
Between 0.4 and 0.8	Fair
Between 0.8 and 1.6	Poor
Greater than 1.6	Very poor

BINNING DATA

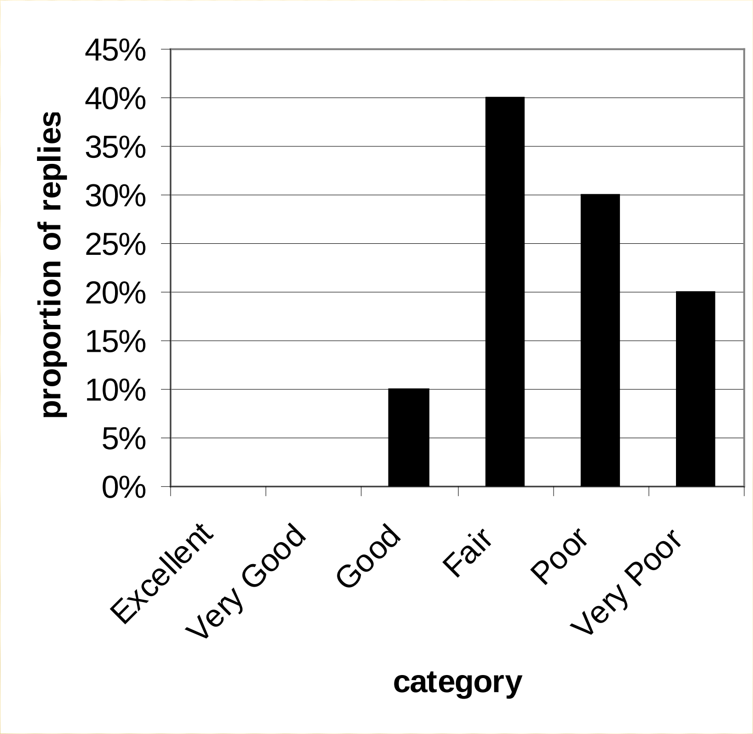
- Now we have a relationship between the numerical output and the natural language categories, what happens if we calculate the amount of FSV data in each of the categories and display it in a histogram?
- The resulting confidence histogram is similar to the proportion of people's opinions.

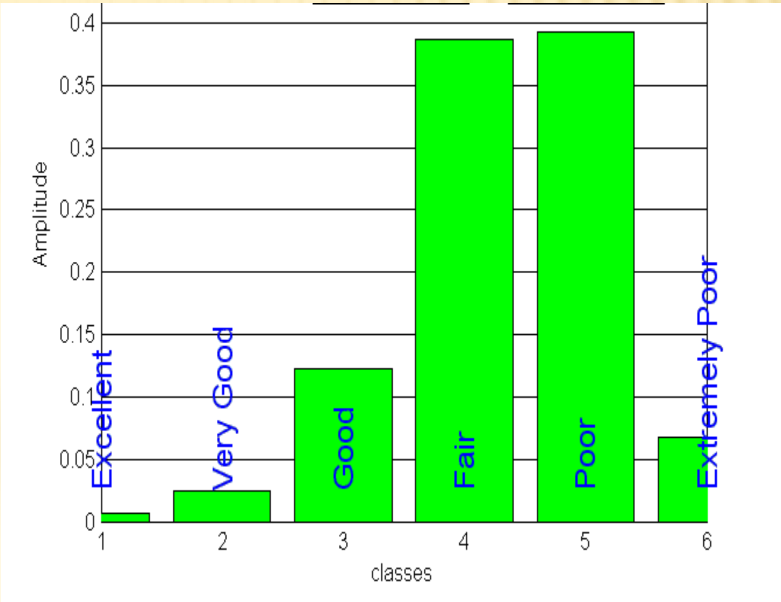
FOR EXAMPLE



Original data

COMPARISON





Engineers

FSV

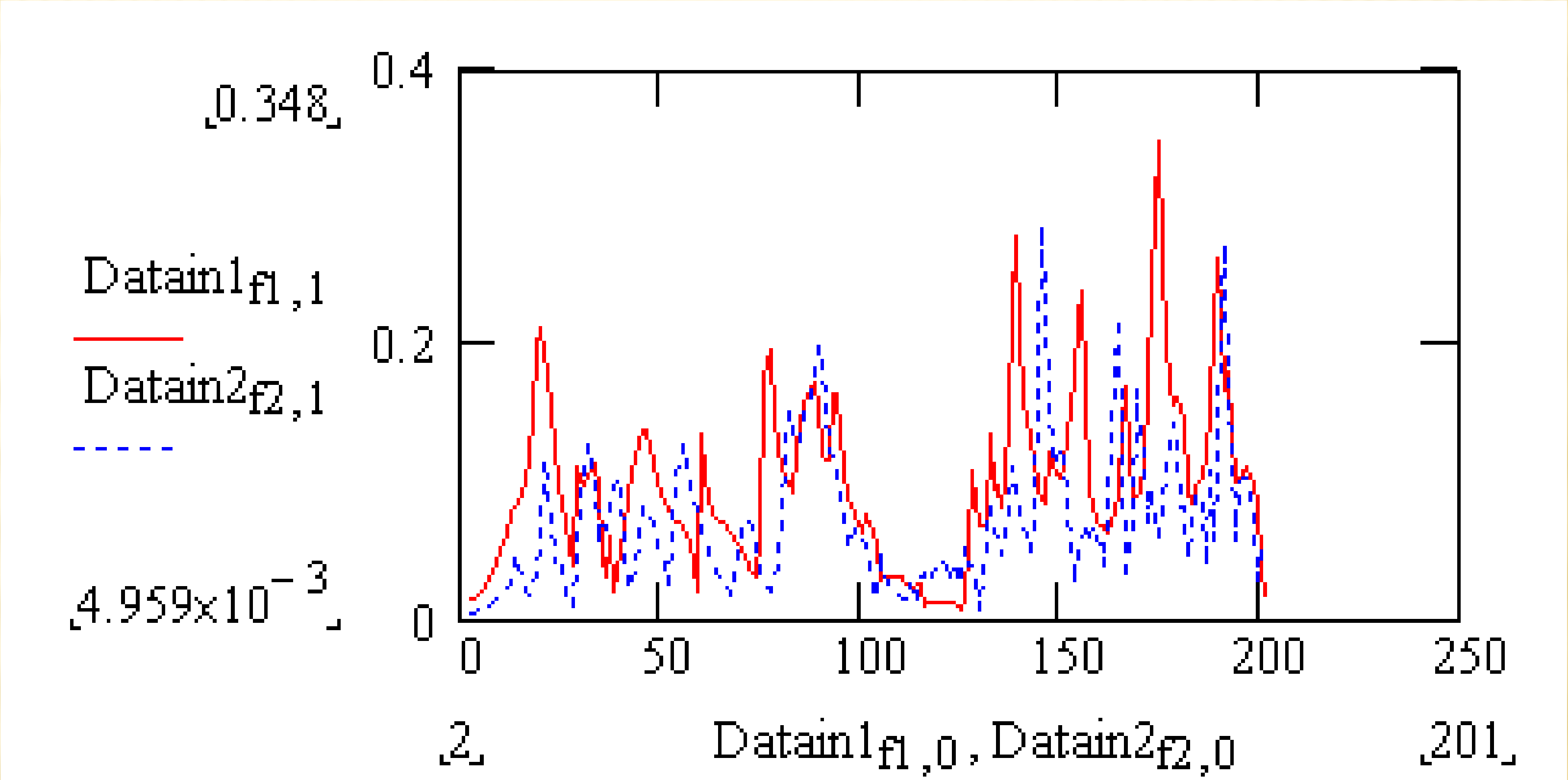
A NOTE ON QUALITY AND ACCEPTABILITY

- The natural language descriptors are there to provide useful ‘pegs’.
- They are not prescriptive measures of absolute quality
- Acceptability is based on an understanding and anticipation of how the system performs.
- Acceptability can be set at any appropriate level – even Very Poor.

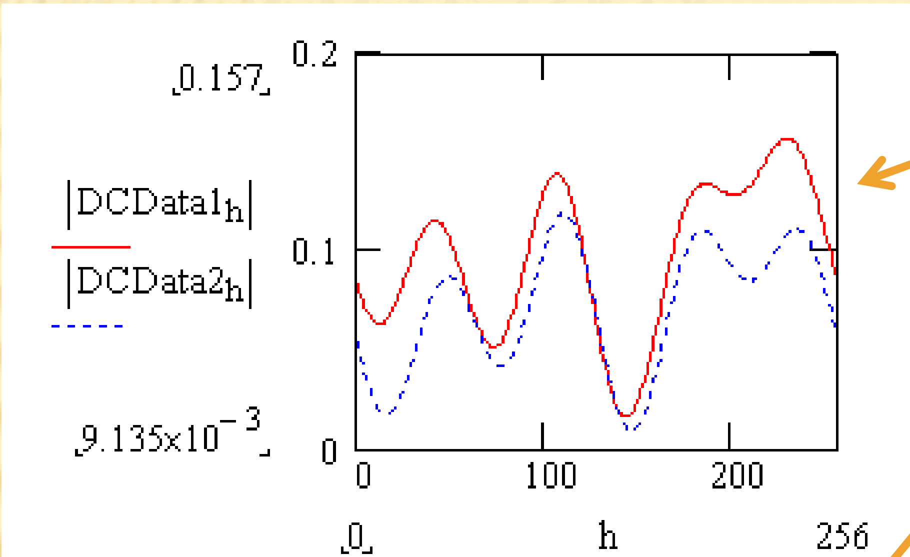
SO FAR …

- It is clear that adequate solution of Maxwell’s equations for serious problems requires the development of modelling tools.
- The validation of those tools so that they can be used with confidence is non-trivial.
- The FSV technique looks like it might be able to do the job.
- Interesting to look at the method in operation.

HERE'S SOME DATA TO COMPARE



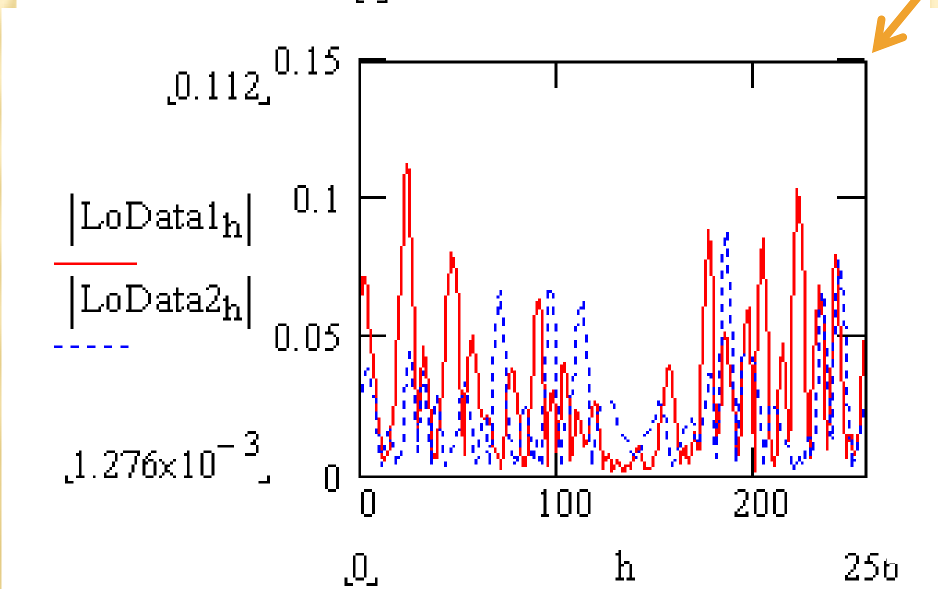
THE 'FILTER' DATA

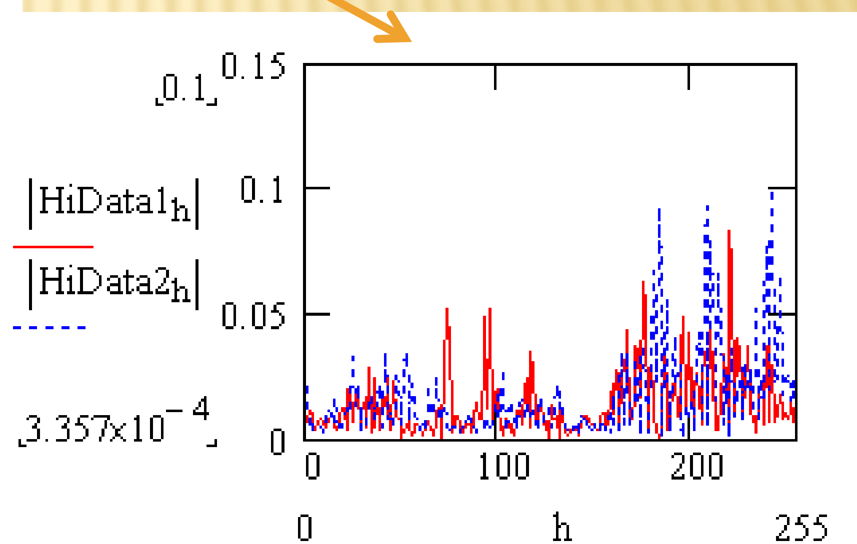


The 'low pass' Data

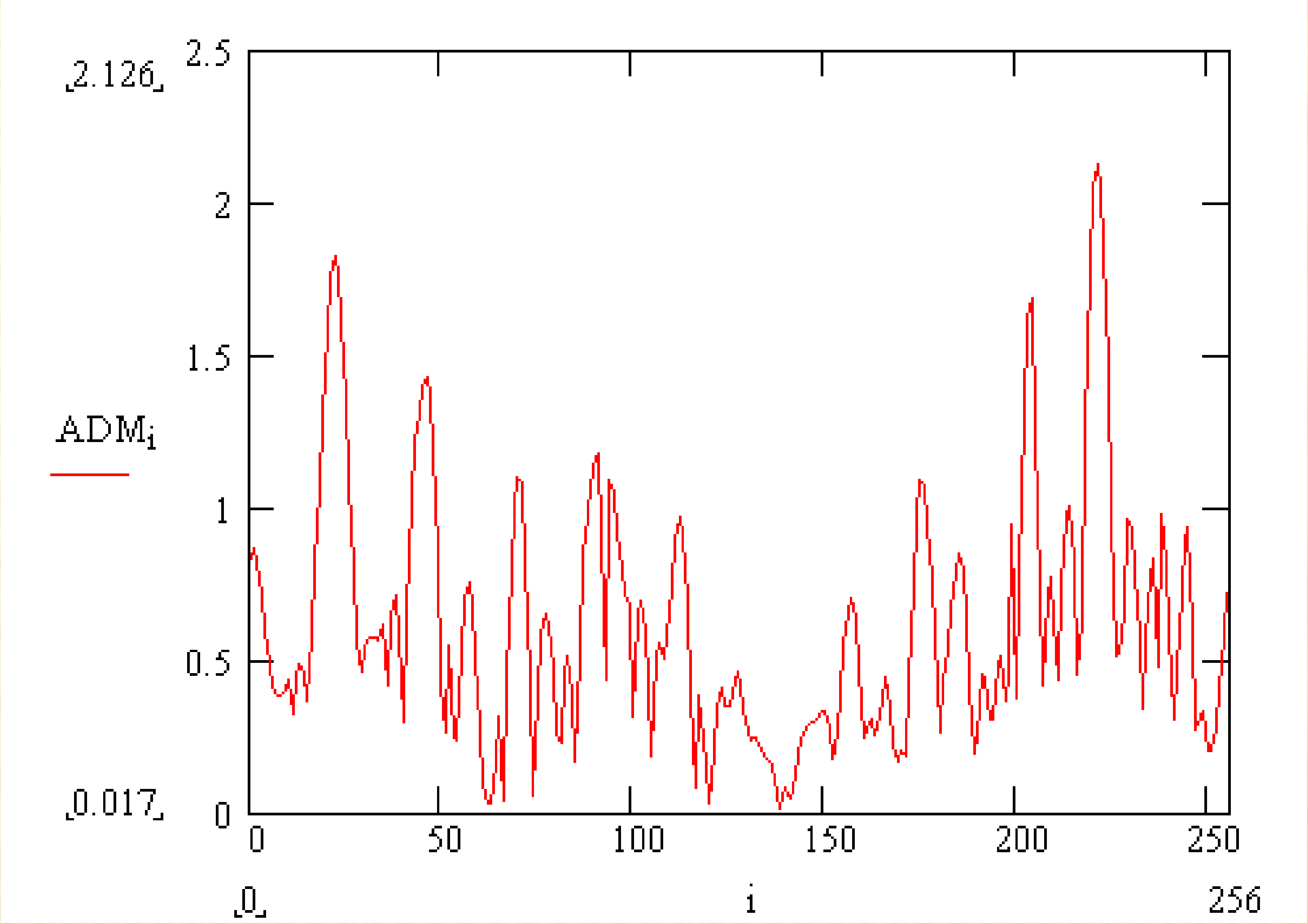
The 'band pass' data

The 'high pass' data

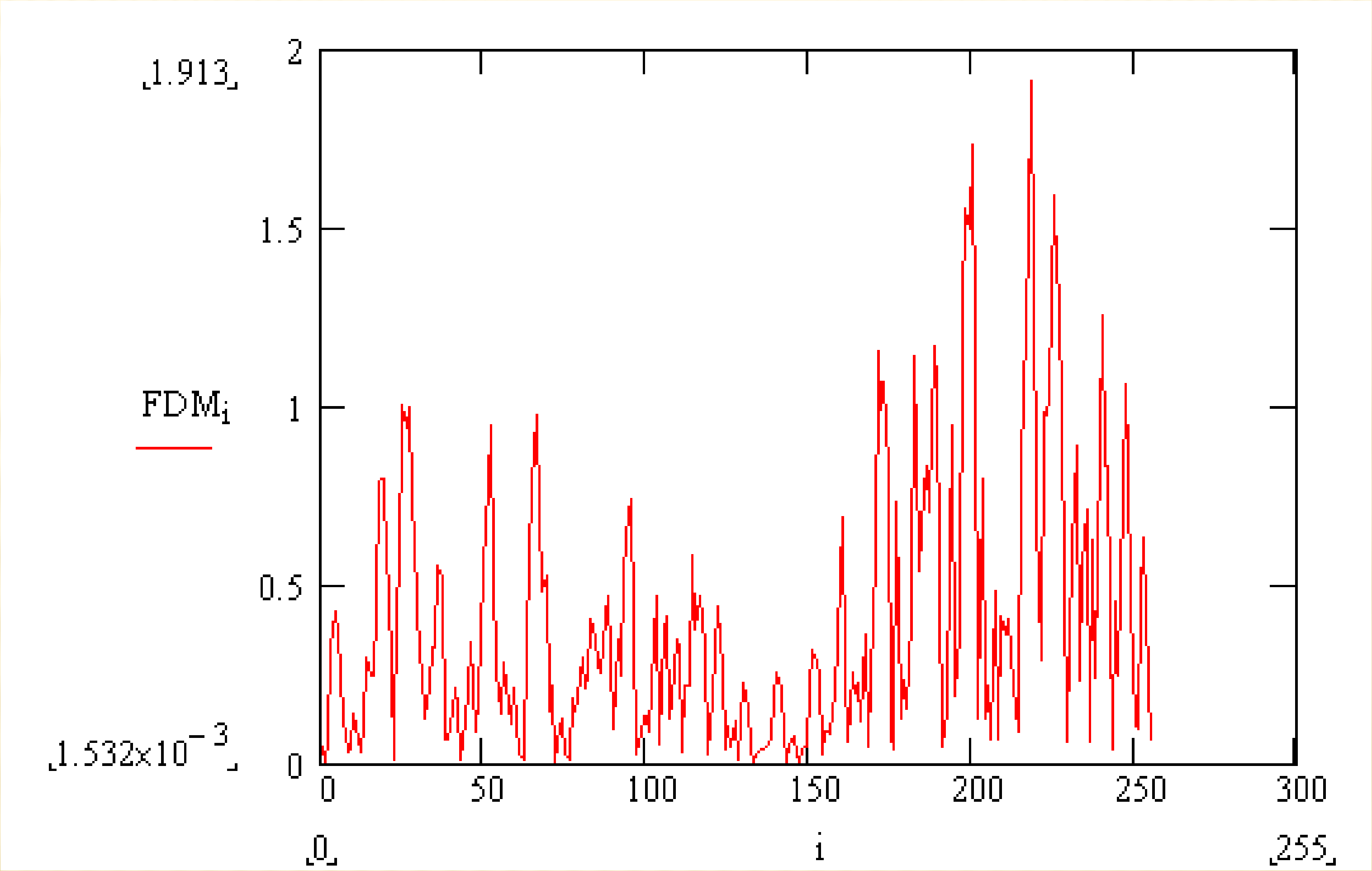




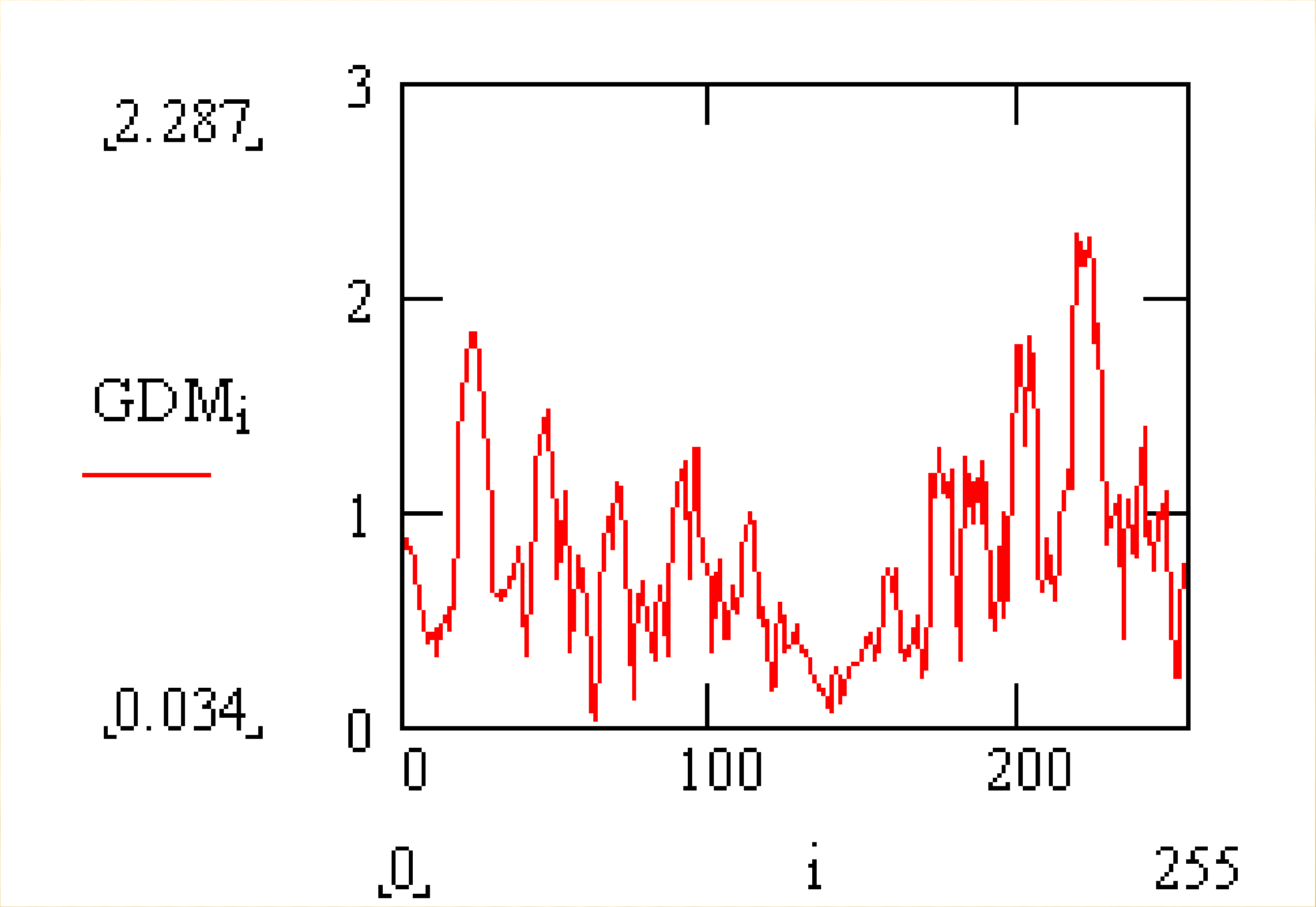
ADM – POINT BY POINT



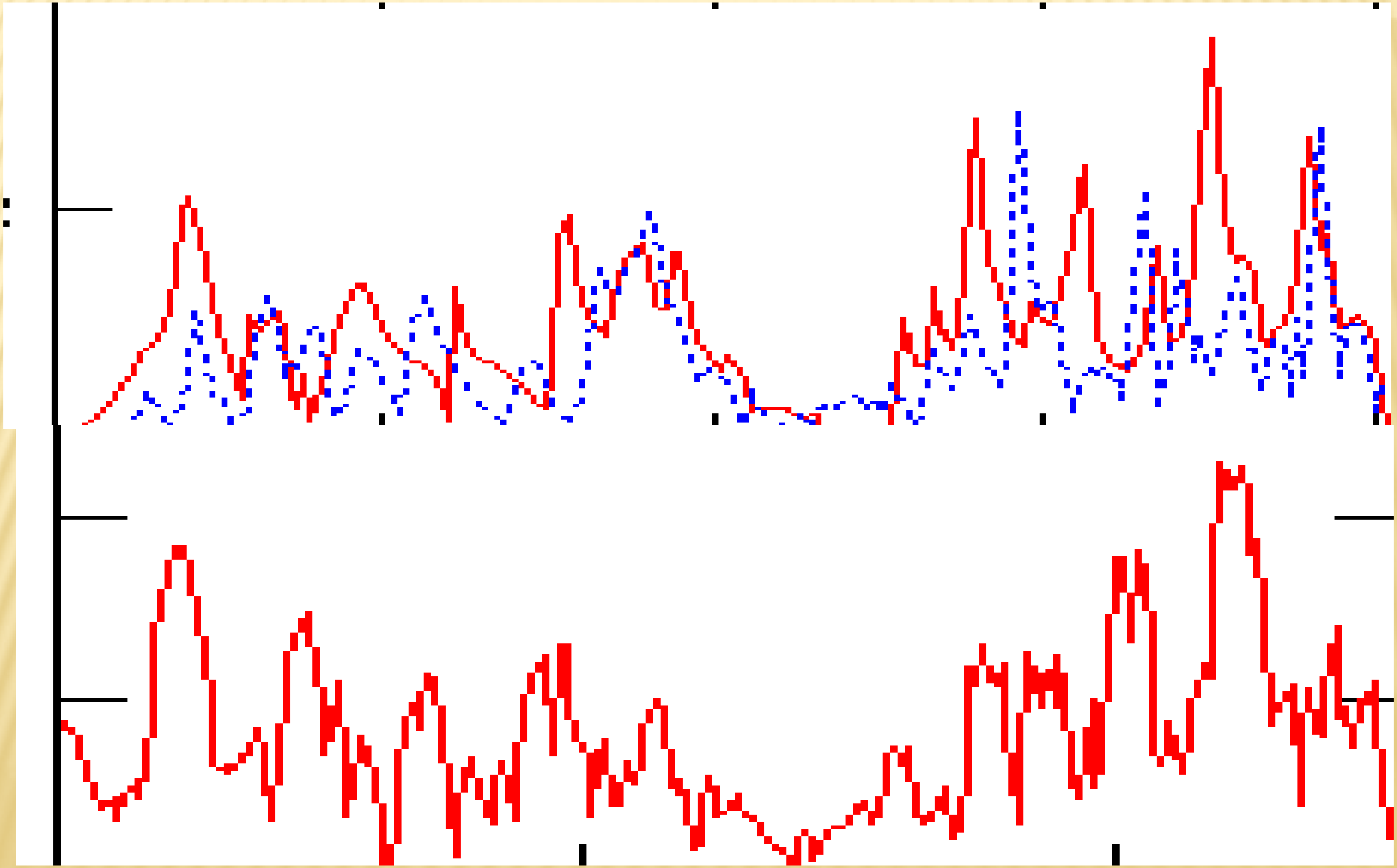
FDM - POINT BY POINT



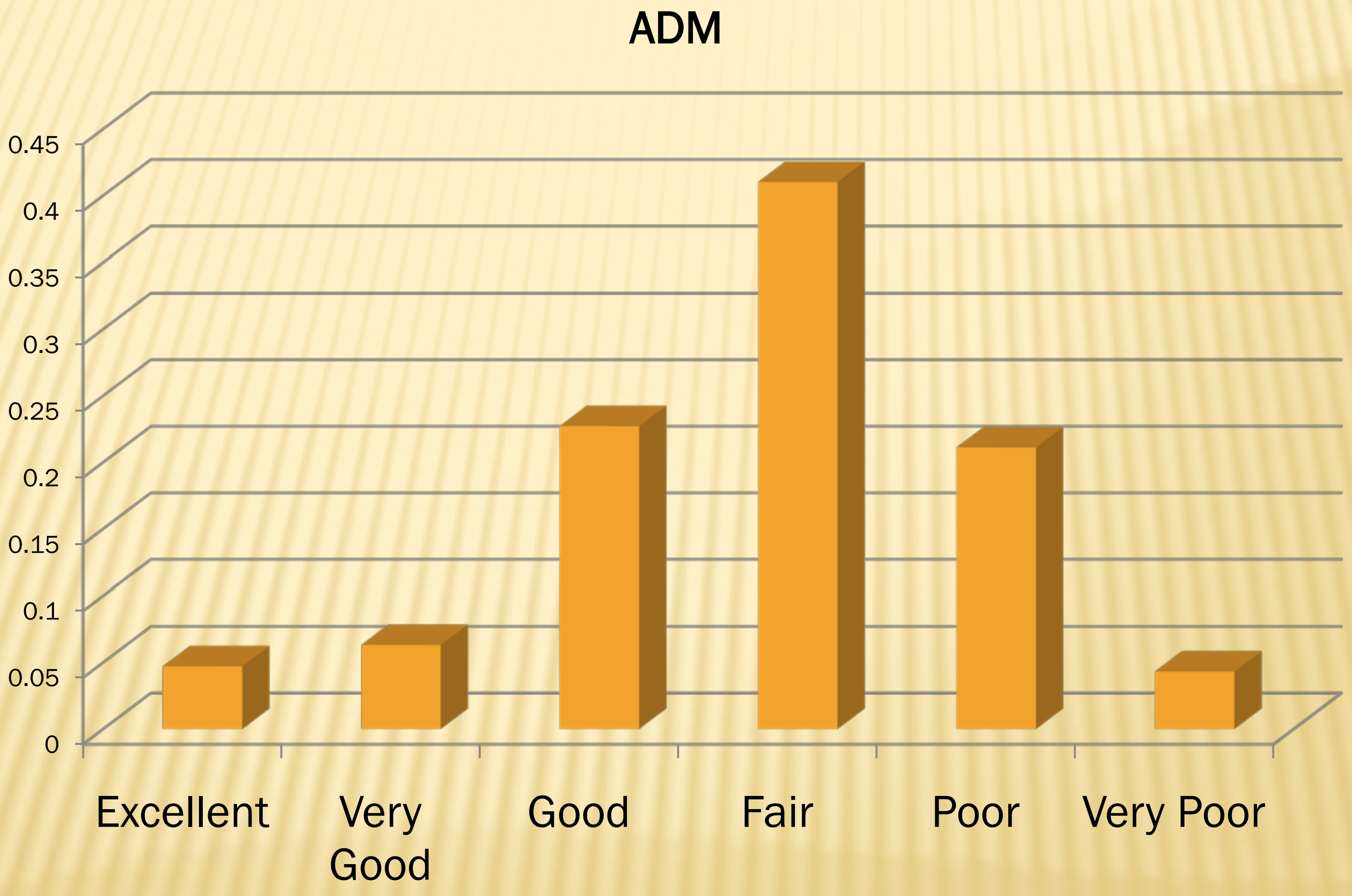
GDM – POINT BY POINT



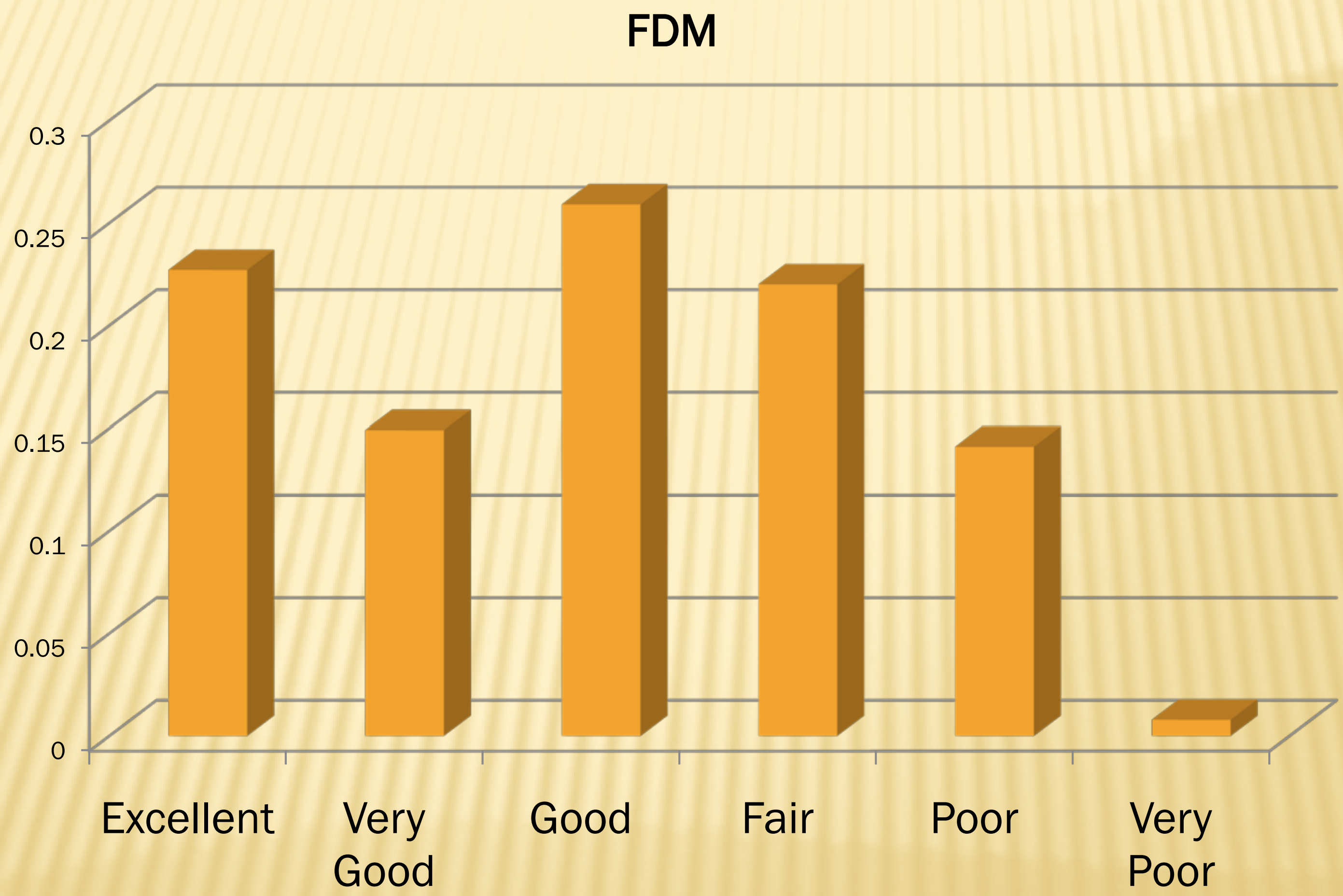
THE COMPARISON



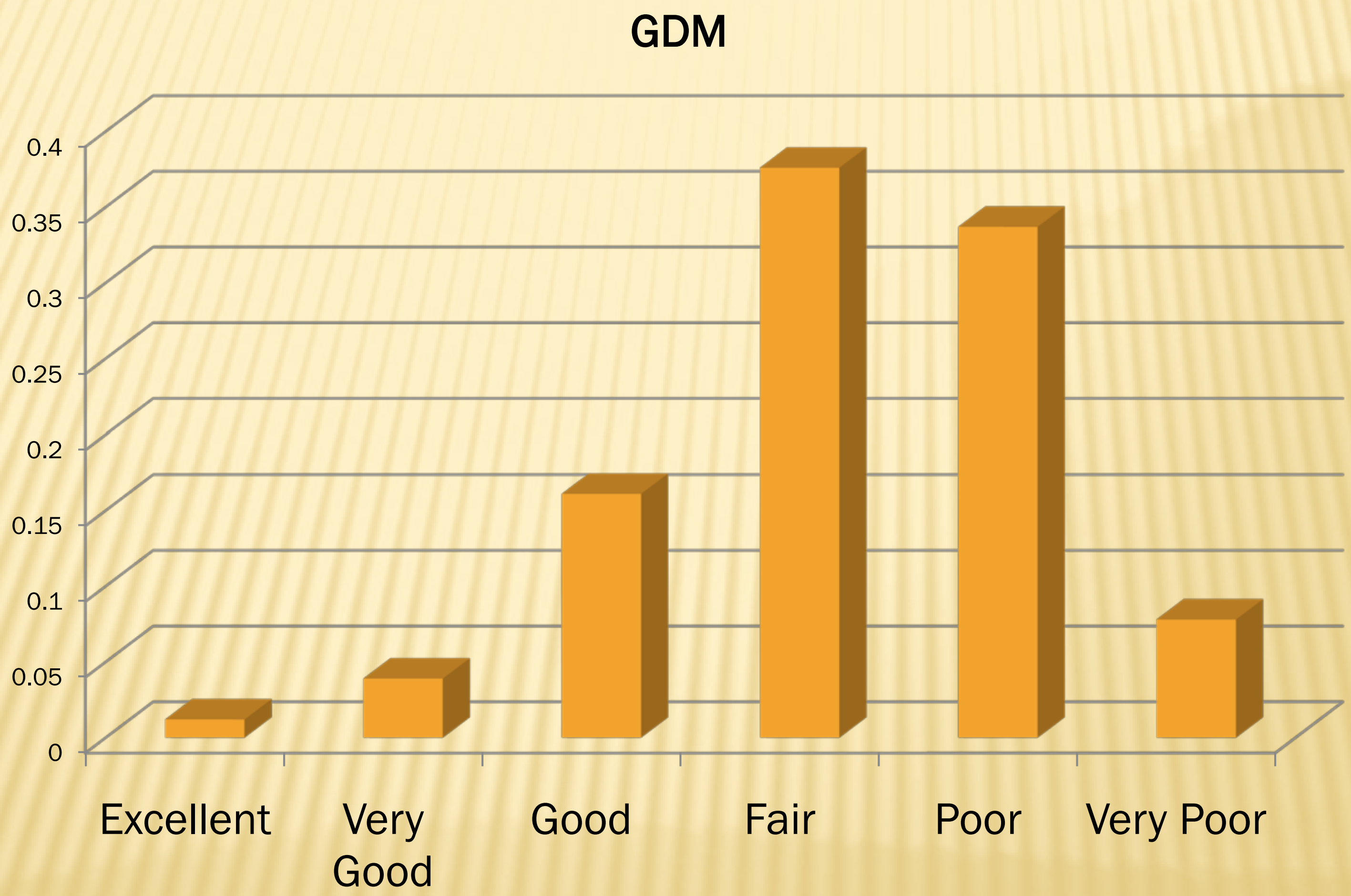
ADM CONFIDENCE



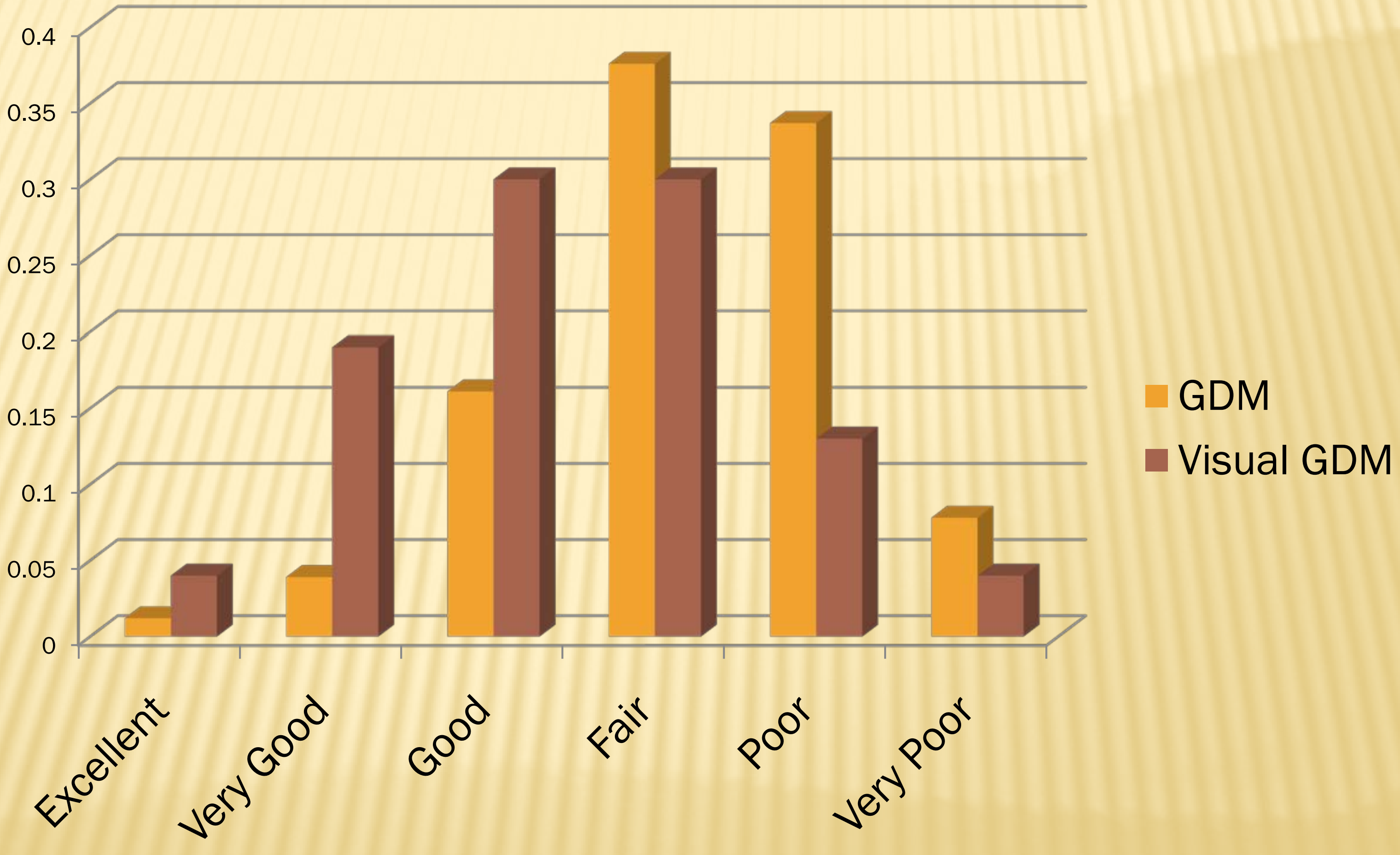
FDM CONFIDENCE



GDM CONFIDENCE



GDM CONFIDENCE COMPARISON



MAKING THIS RELEVANT - STANDARDS

NEW STANDARD TO CONSIDER

- IEEE Standard for Validation of Computational Electromagnetics Computer Modeling and Simulation.
- Published February '09.
- Standard plus good practice guide (out for vote soon)
- IEEE1597
  - 1597.1 = Standard
  - 1597.2 = Good Practice Guide

SCOPE

This standard defines a method to validate computational electromagnetics (CEM) computer modeling and simulation (M&S) techniques, codes, and models.

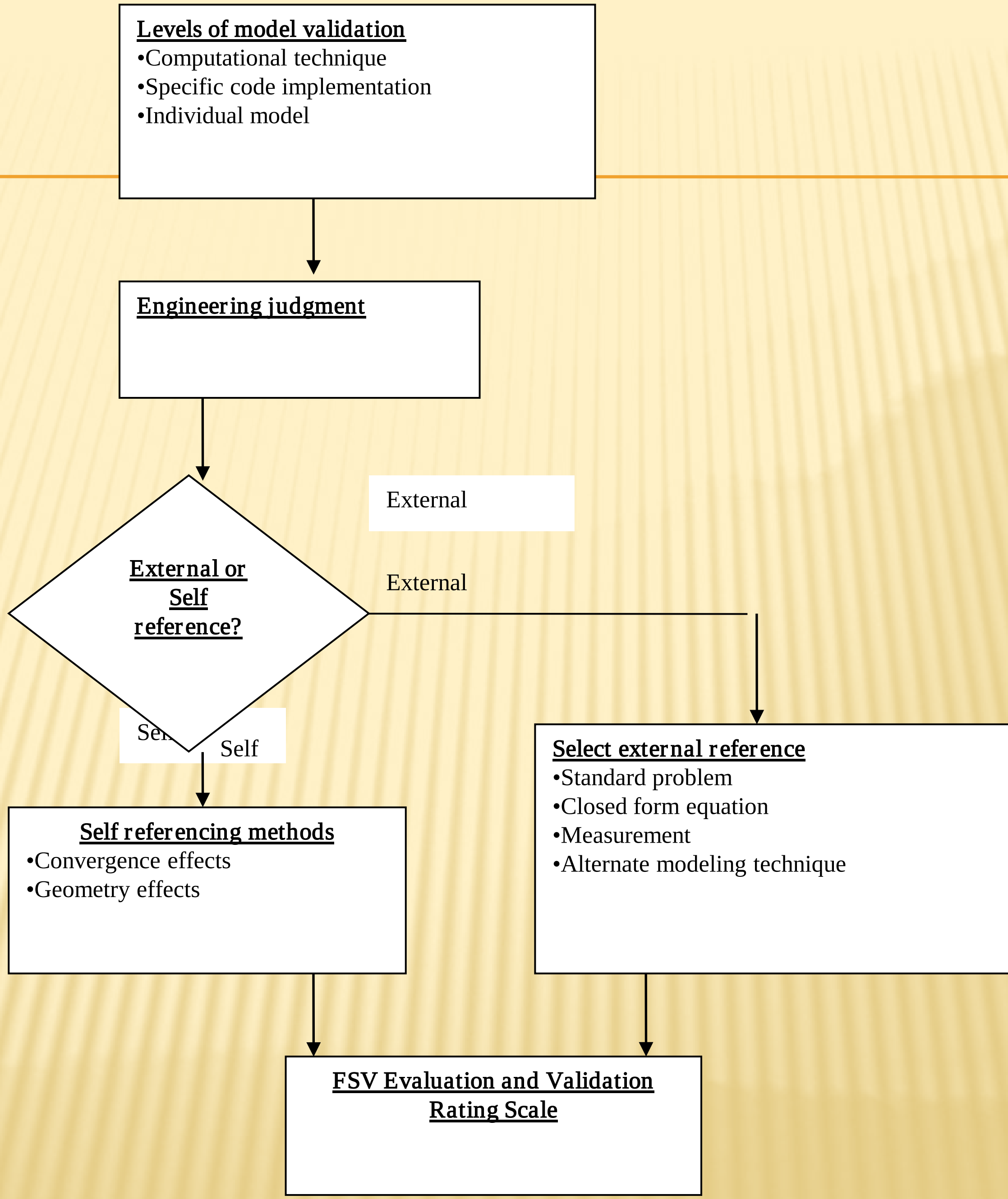
It is applicable to a wide variety of electromagnetic (EM) applications including but not limited to the fields of electromagnetic compatibility (EMC), radar cross section (RCS), signal integrity (SI), and antennas.

Validation of a particular solution data set can be achieved by comparison to the data set obtained by measurements, alternate codes, canonical, or analytic methods.

PURPOSE

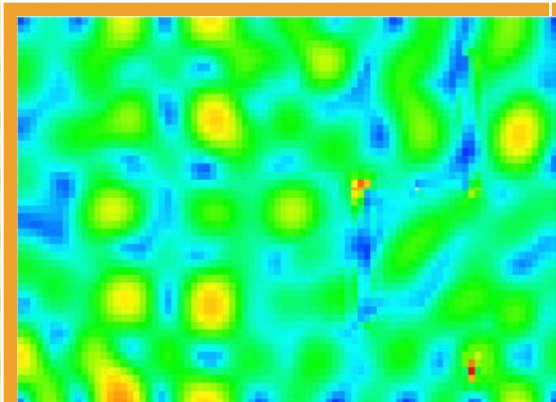
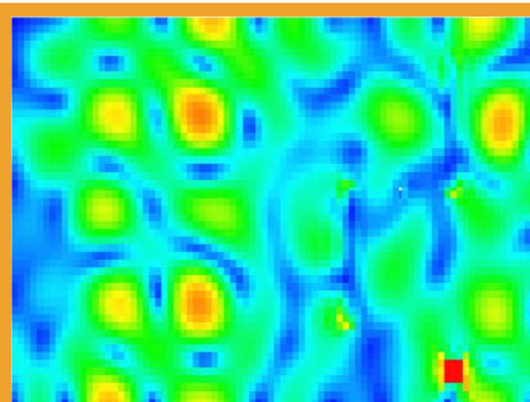
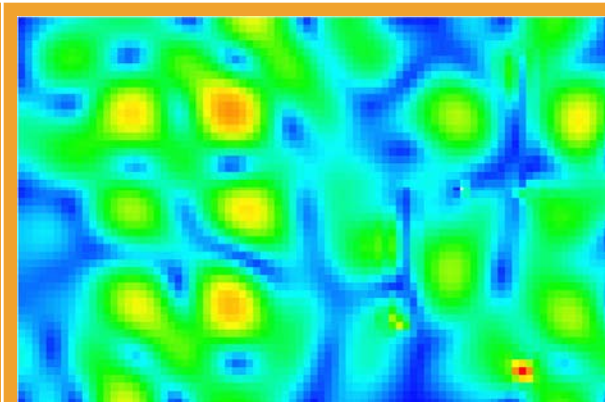
This standard provides a formal mechanism for comparing the results of various CEM techniques, codes, and models in a repeatable way against a set of “golden” benchmarks, including standard validation and canonical problem sets. These data are based on theoretical formulations, or obtained as a result of performing high-quality measurements and, in certain cases, based on accurate analyses that have undergone and withstood peer validation.

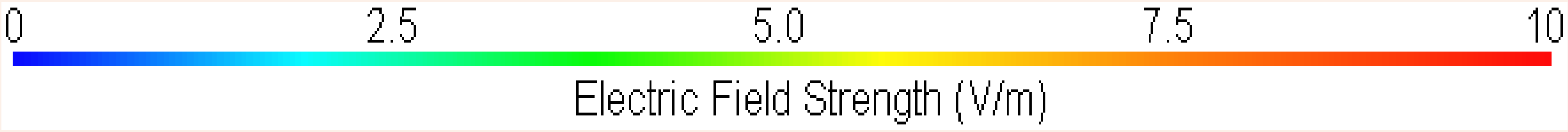
VALIDATION FLOW CHART


Levels of model validation
•Computational technique
•Specific code implementation
•Individual model
Engineering judgment
External or Self reference?
External
External
Self
Self referencing methods
•Convergence effects
•Geometry effects
Select external reference
•Standard problem
•Closed form equation
•Measurement
•Alternate modeling technique
FSV Evaluation and Validation Rating Scale

WHAT'S NEXT?

How can these be compared to gauge convergence?

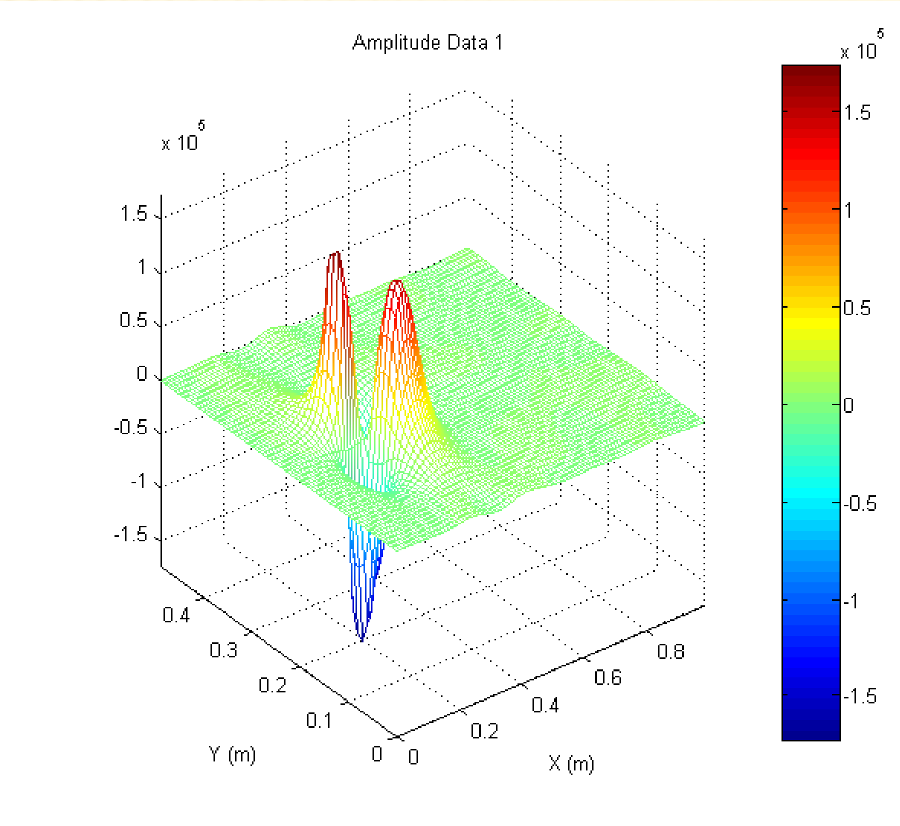
		
Eight thousand time steps	Eighty thousand time steps	Eight hundred thousand time steps

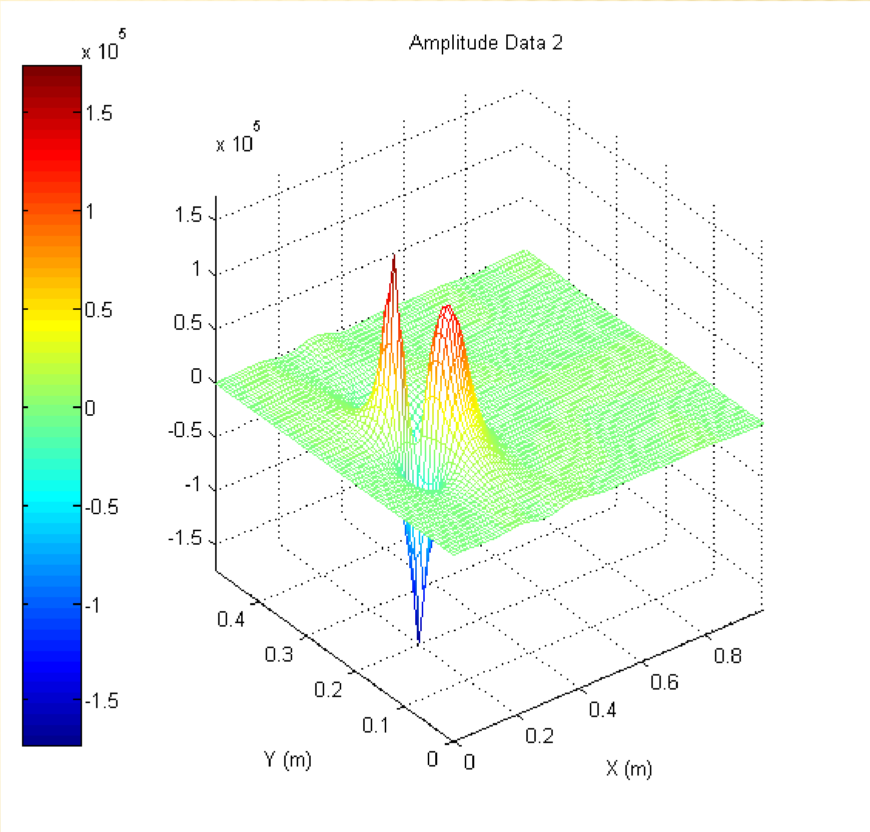


DIFFICULTIES

- Not easy for people to judge the performance of 2D, virtually impossible for 3D and how can someone visualize 4D?
- FSV can be extended by using *n*D Fourier Transforms. Rather more taxing to design the filters when one dimension can be hundreds (or thousands) of points long and another can be, perhaps 10 points.
- The subject of an ongoing project.

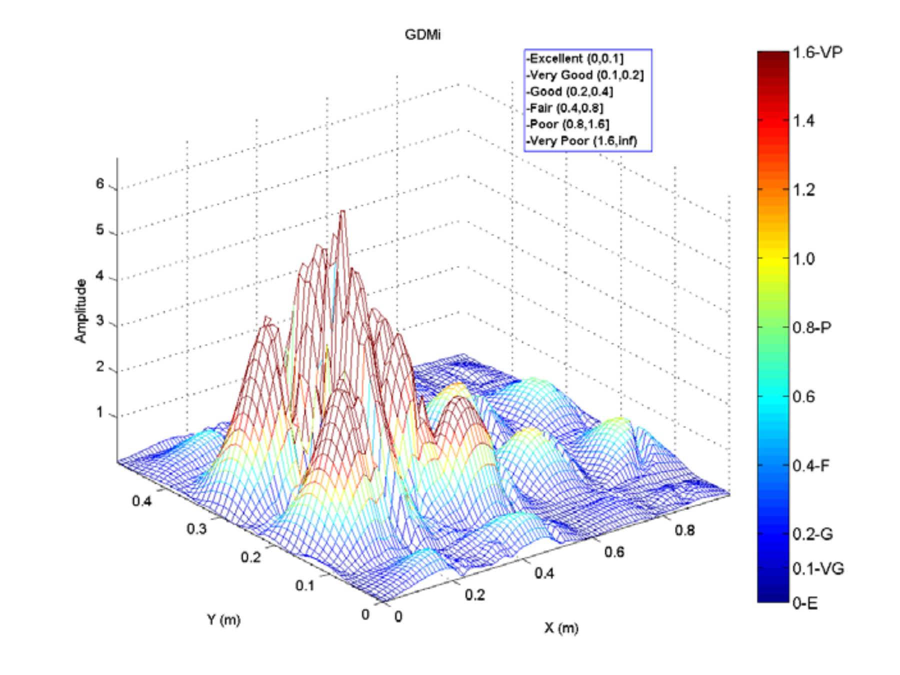
2D FSV SO FAR.



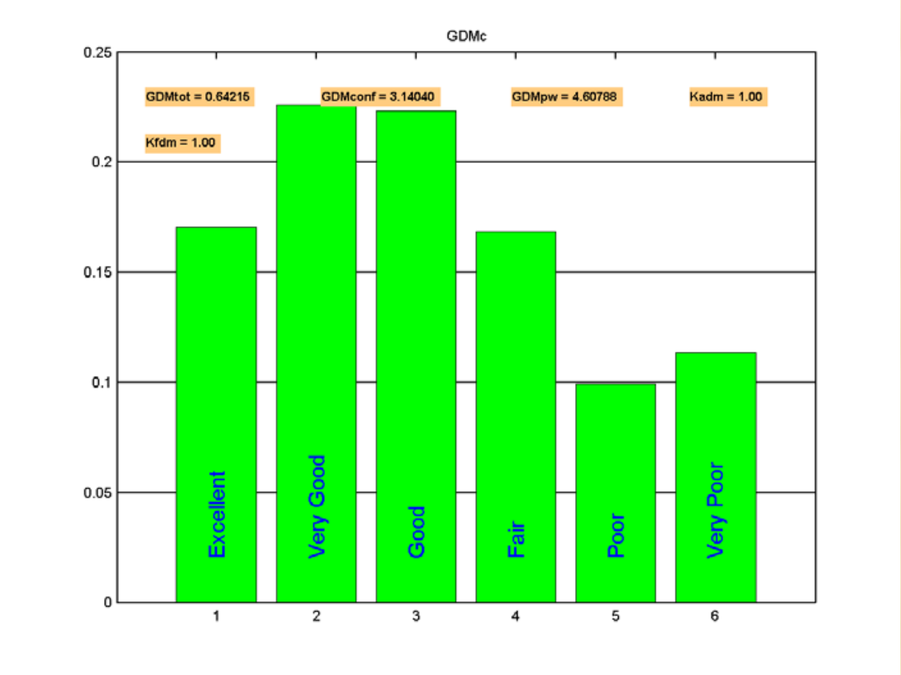


Two instants of time for a propagating pulse

GDM



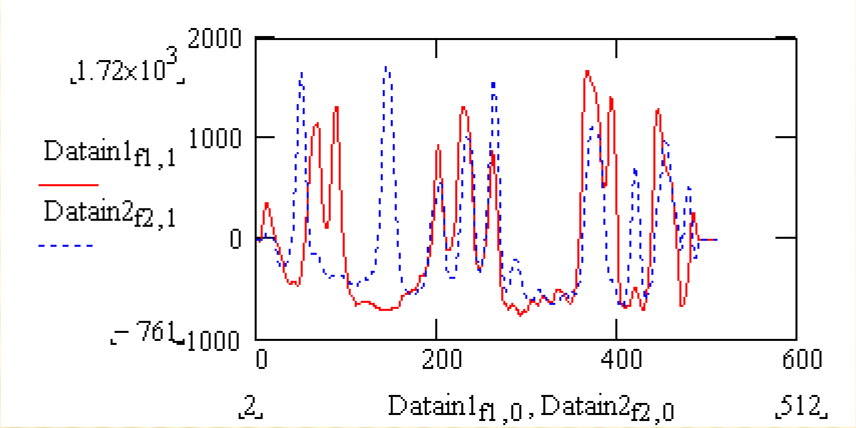
GDMi
-Excellent (0,0.1]
-Very Good (0.1,0.2]
-Good (0.2,0.4]
-Fair (0.4,0.8]
-Poor (0.8,1.6]
-Very Poor (1.6,inf)
Amplitude
Y (m)
X (m)
1.6-VP
1.4
1.2
1.0
0.8-P
0.6
0.4-F
0.2-G
0.1-VG
0-E



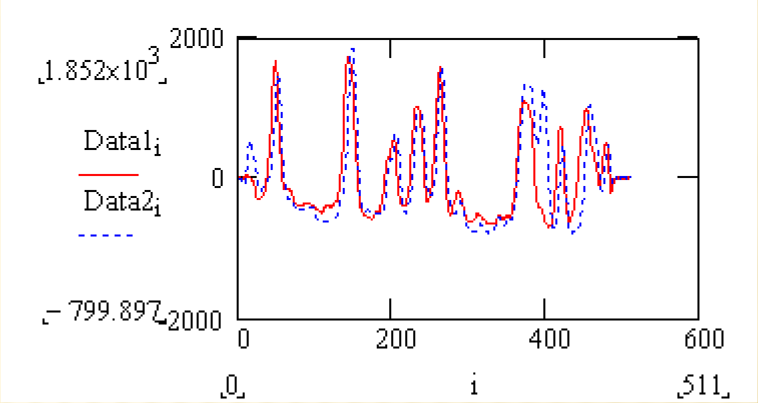
GDMc
GDMtot = 0.64215
GDMconf = 3.14040
GDMpw = 4.60788
Kadm = 1.00
Kfdm = 1.00
Excellent
Very Good
Good
Fair
Poor
Very Poor

AND FINALLY – OTHER POSSIBLE AREAS

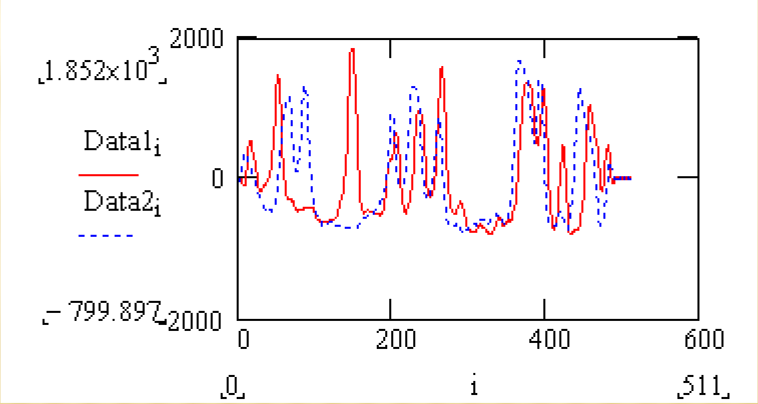
- In deference to 25 years of genetic fingerprinting?
- Three bird offspring – which is the cuckoo?



#1 vs #2, GDM = 1.98



#2 vs #3, GDM = 0.81



#3 vs #1, GDM = 1.43

THE FINAL SLIDE (HONESTLY!)

- Electromagnetics is useful but, in practice, computational implementations are most useful.
- These need to be validated.
- Historical (by-eye) validation is giving way to something more formal.
- FSV is the method of choice
- Still plenty of work to do.

I LIED ABOUT THAT BEING THE LAST SLIDE

Thank you