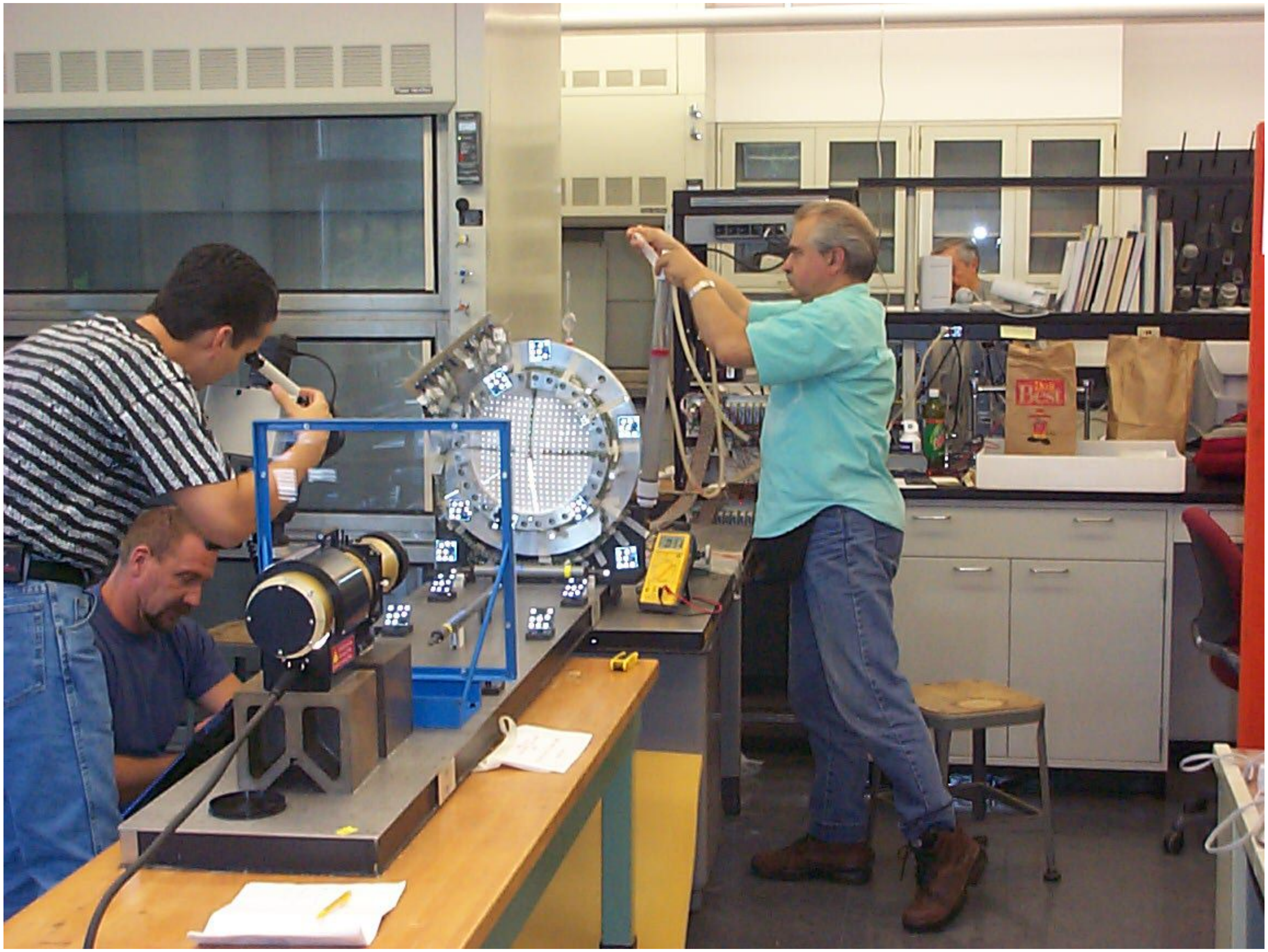
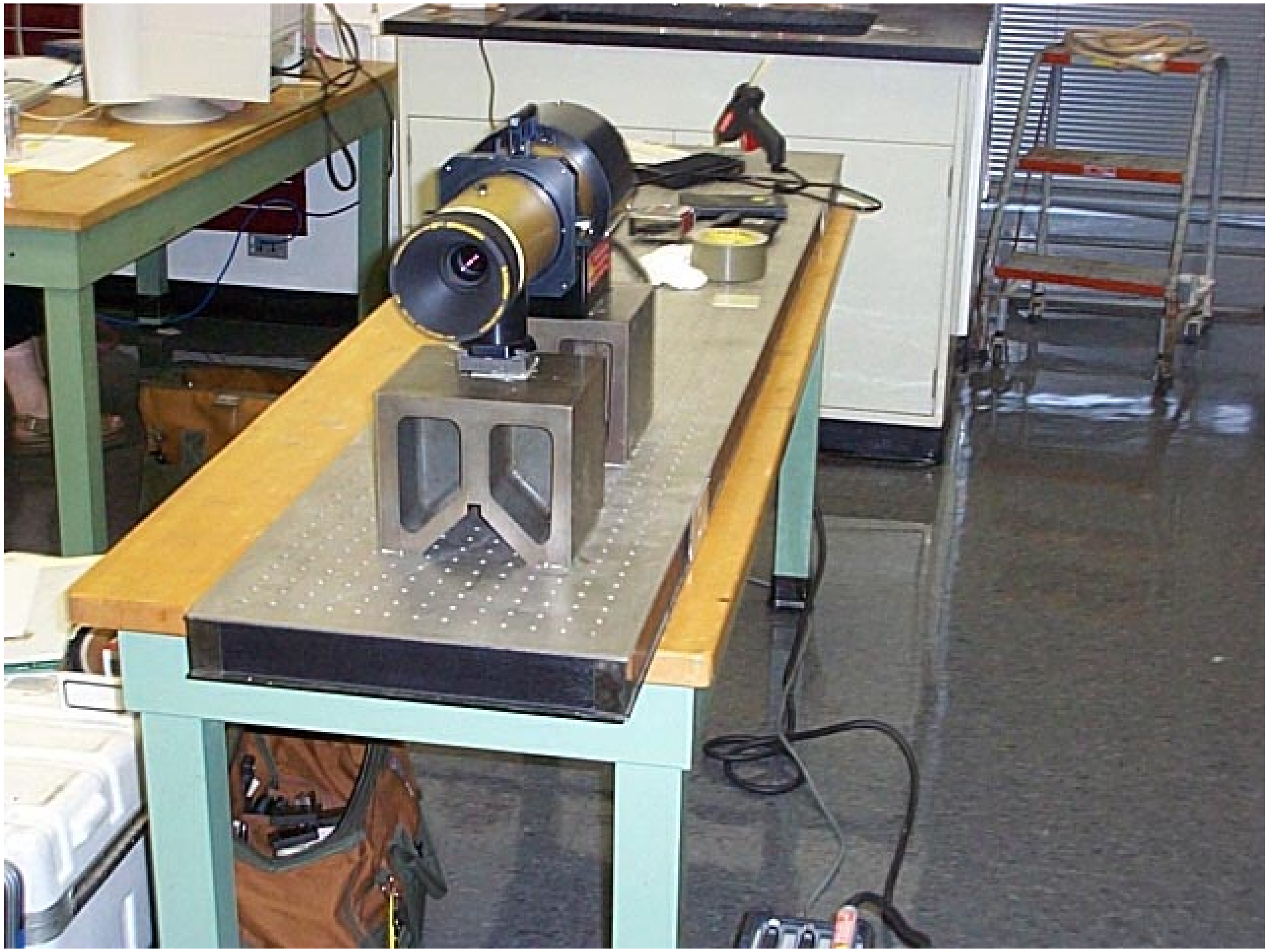
Mucool history of photogrammetry

- Compare the window's *performance* to FEA
- Observe *characteristics* of the window's performance
- Compare the window's *shape and thickness* to design specifications

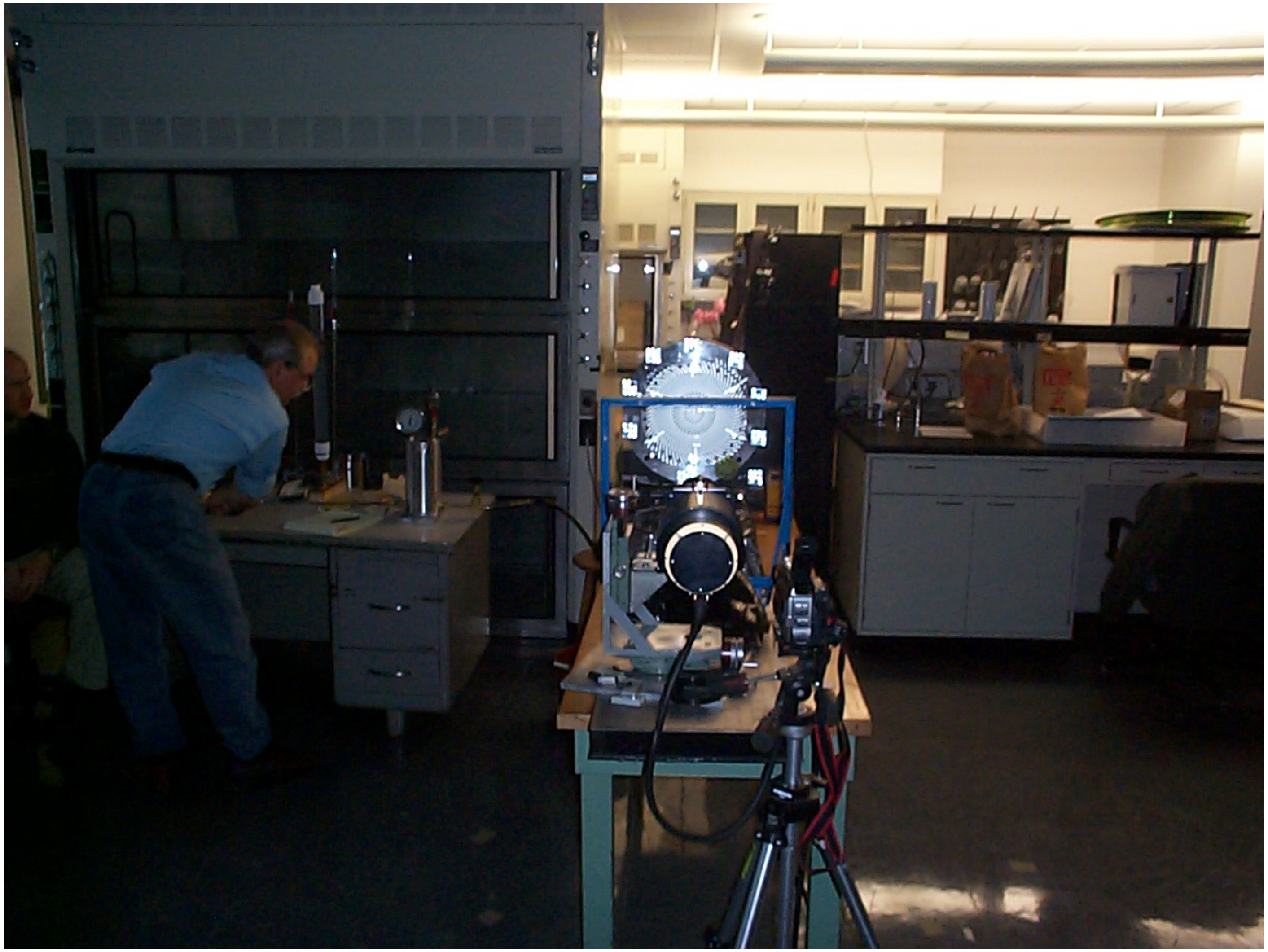
Photogrammetry setup



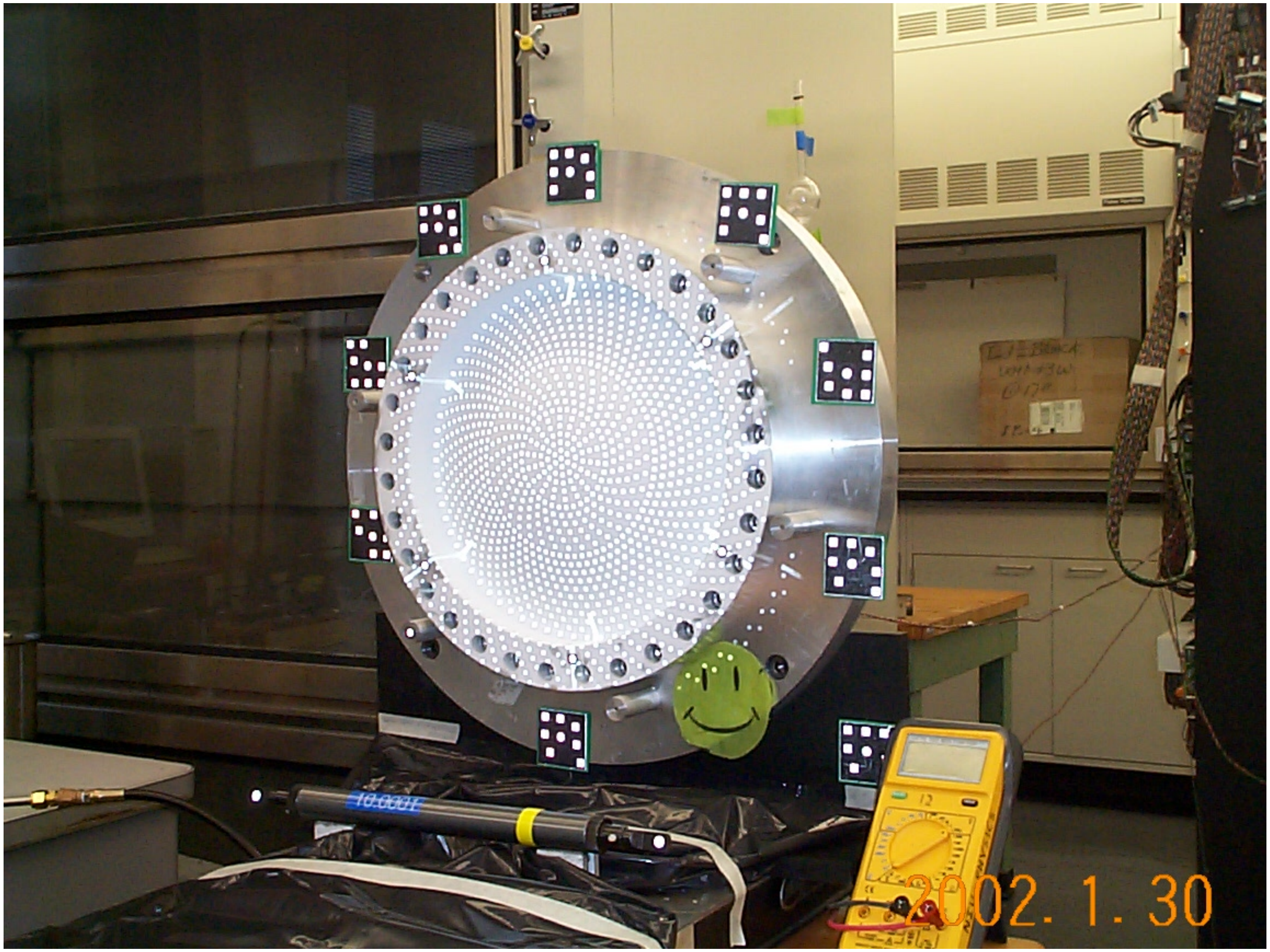
Pro-Spot projector



Projecting targets



Targets



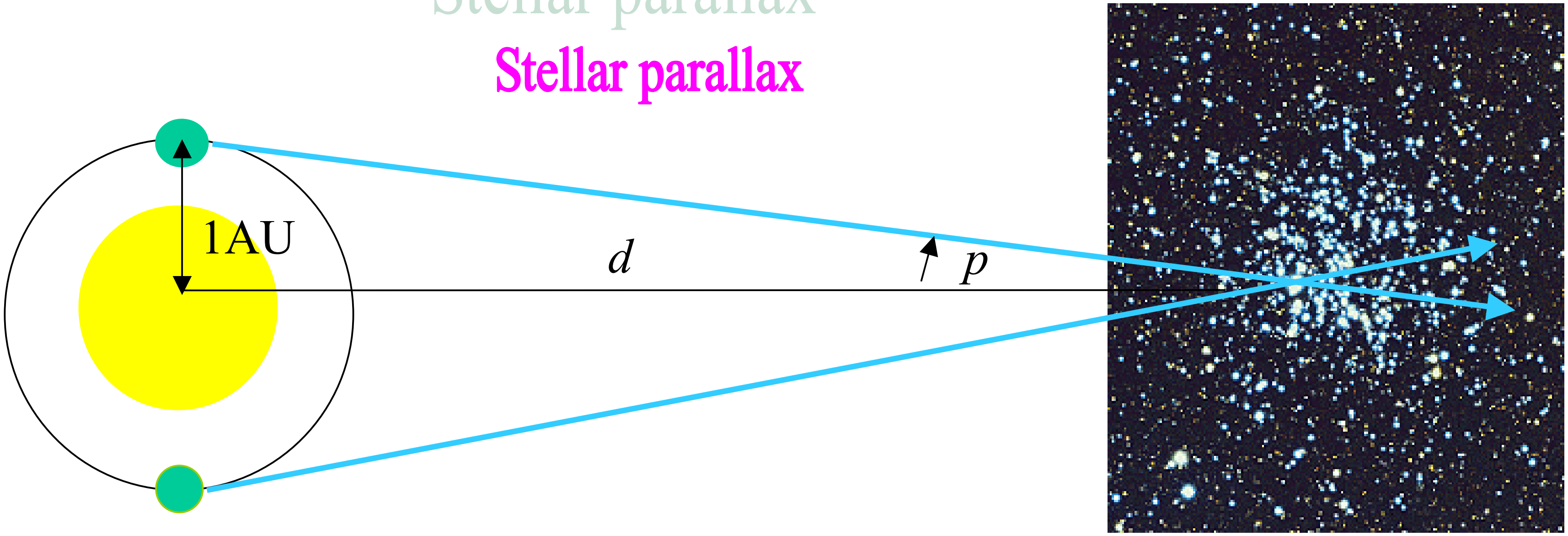
How does photogrammetry work?

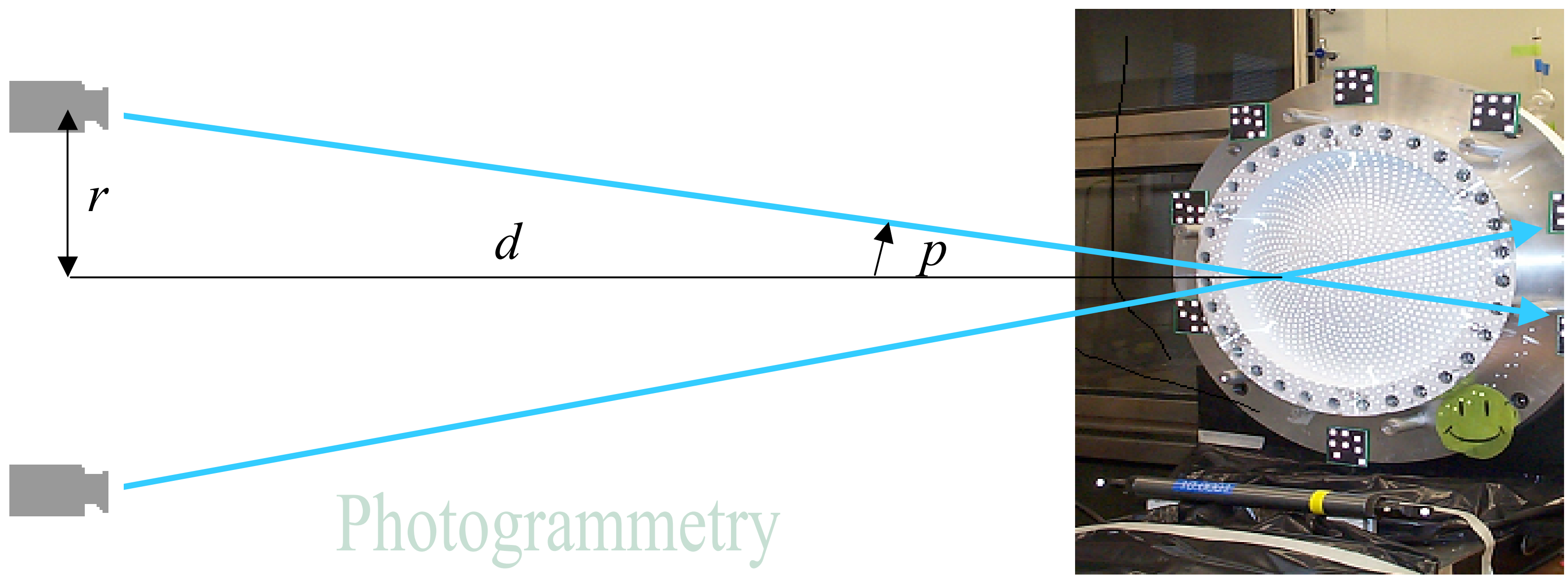
How does photogrammetry work?

Parallax

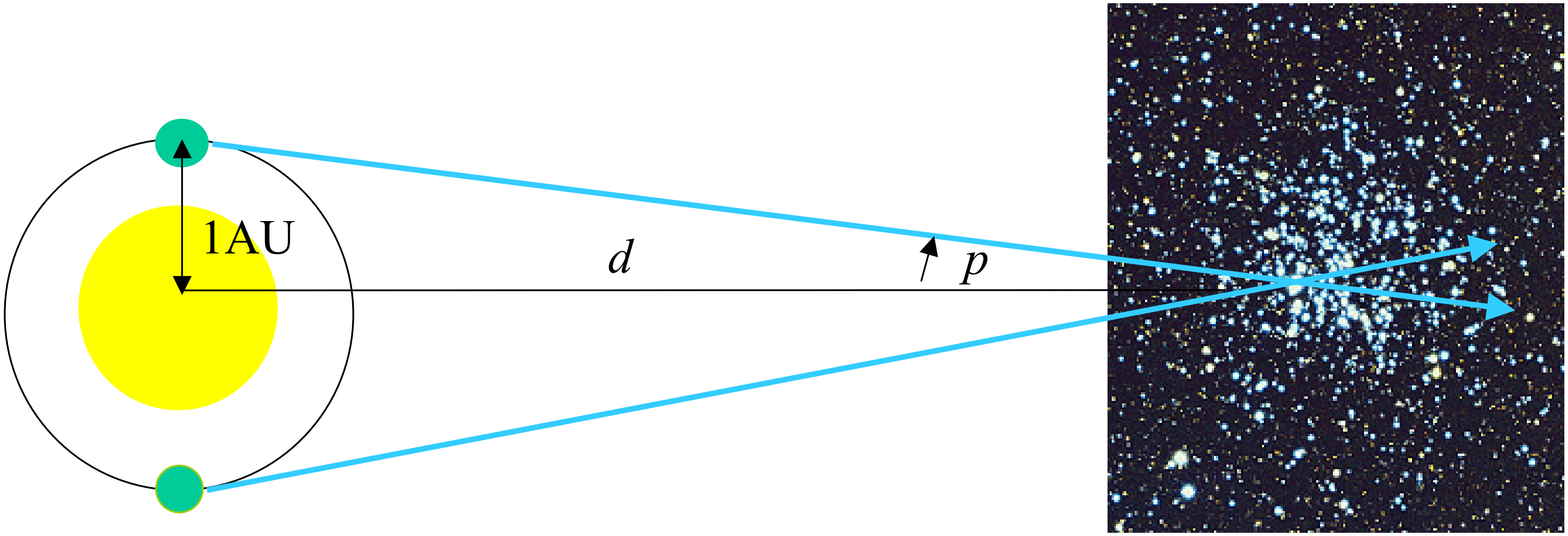
Parallax

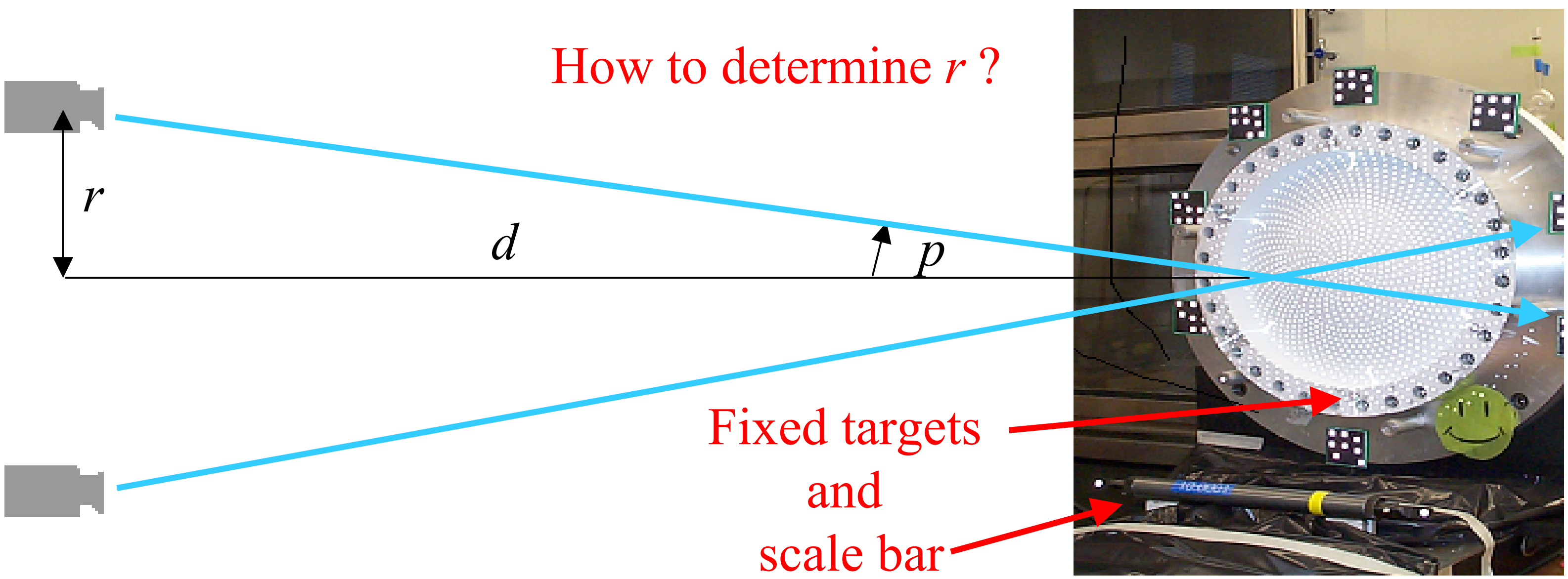
Stellar parallax
Stellar parallax

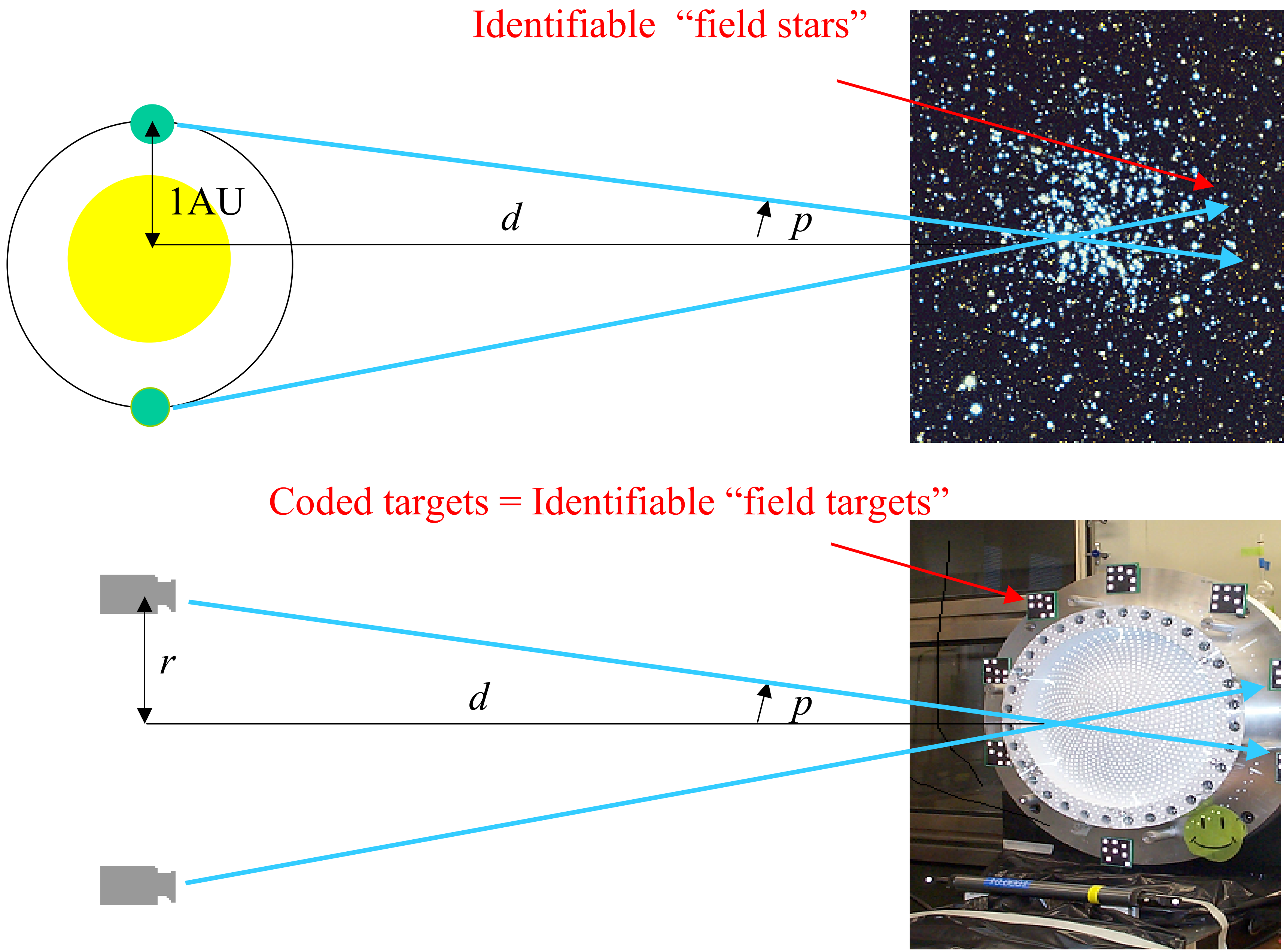




Photogrammetry
Photogrammetry


1AU
d
p


How to determine r ?
r
d
p
Fixed targets
and
scale bar

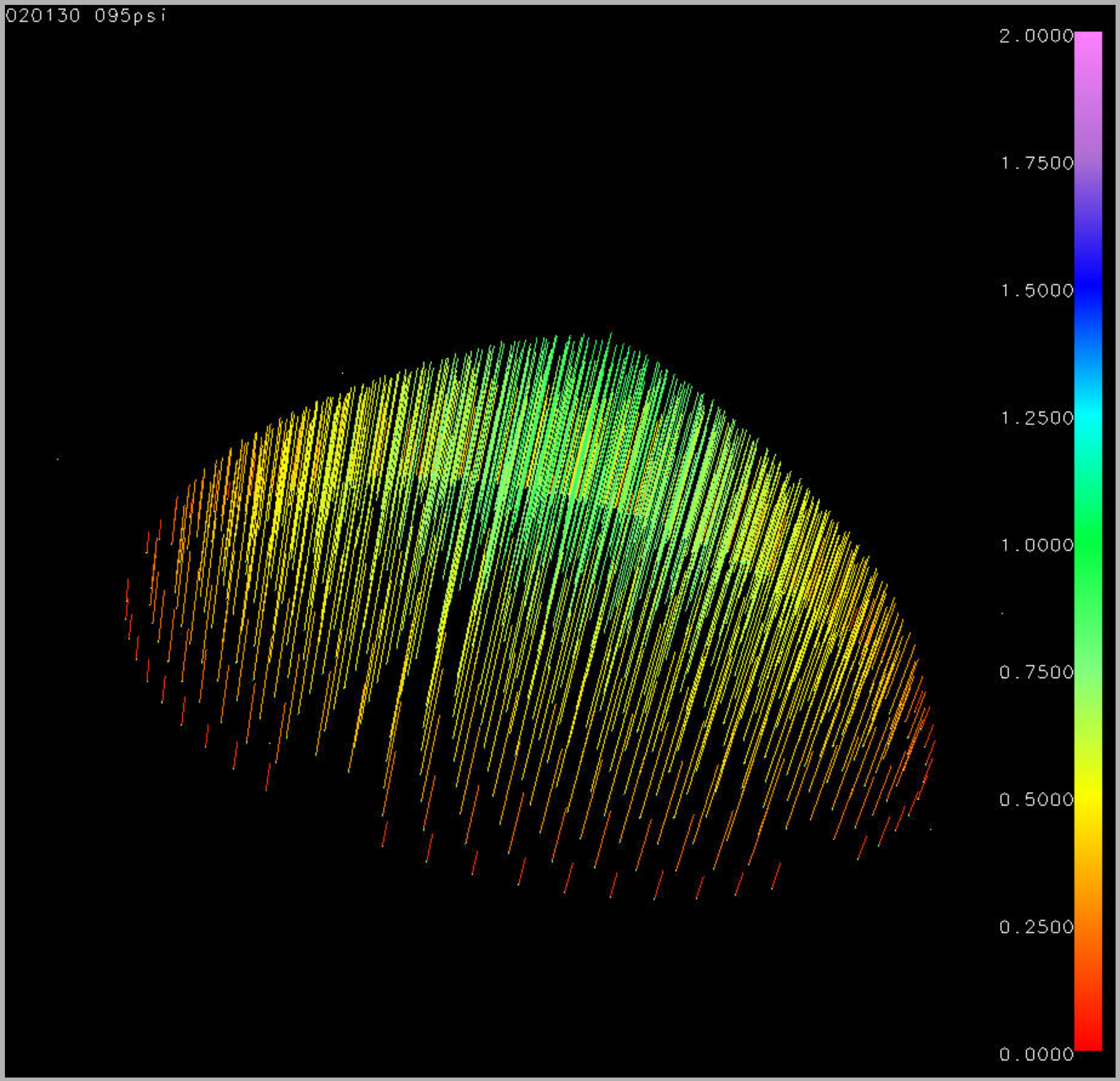

Identifiable "field stars"
1AU
d
p
Coded targets = Identifiable "field targets"
r
d
p

Mucool history of photogrammetry

- Compare the window's *performance* to FEA
- Observe *characteristics* of the window's performance
- Compare the window's *shape and thickness* to design specifications

Create an "animation" of the deformation of the window using whisker plots

Display the *change* in the surface from the initial, unstressed shape

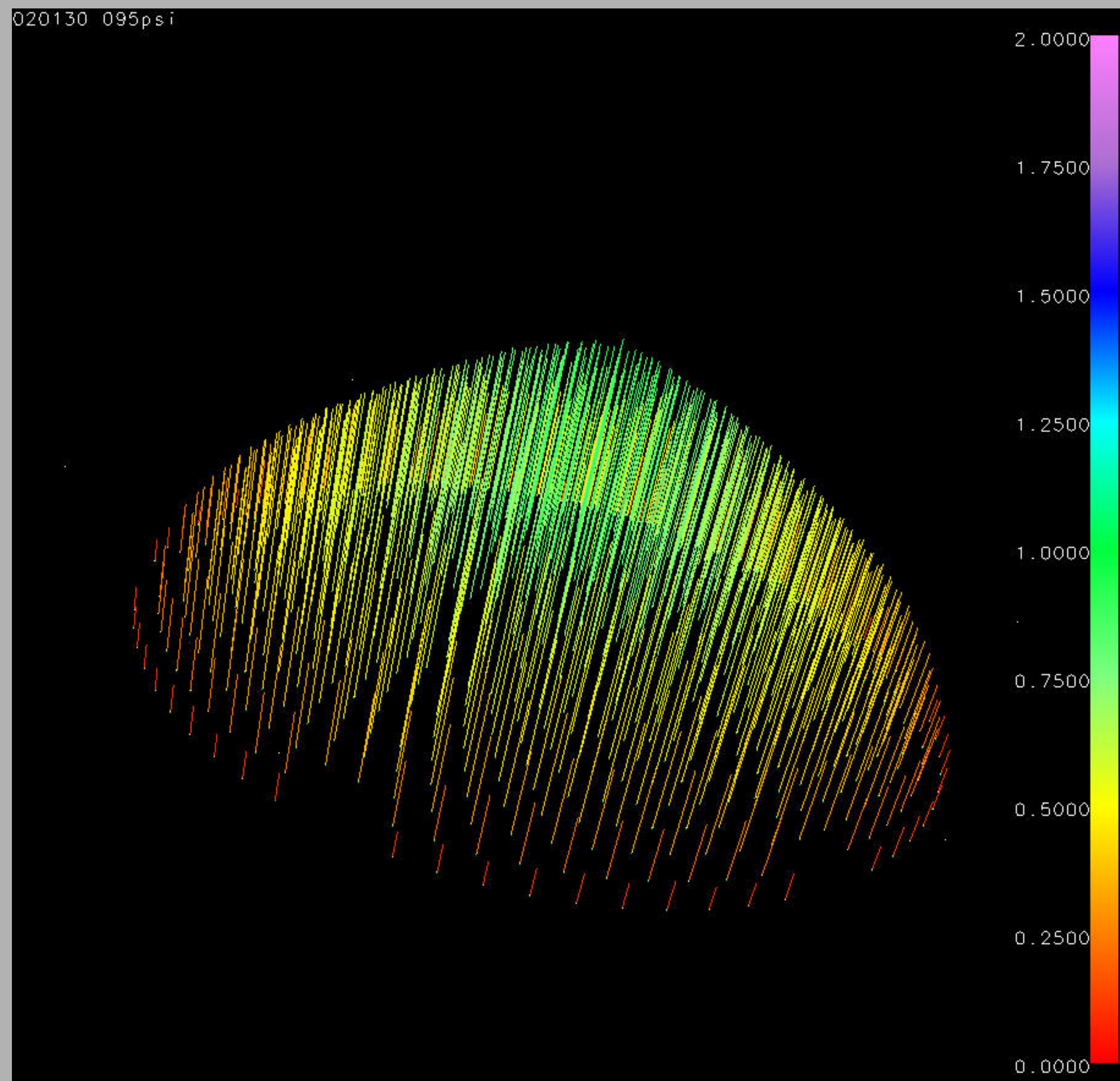


Window 3

Pressure

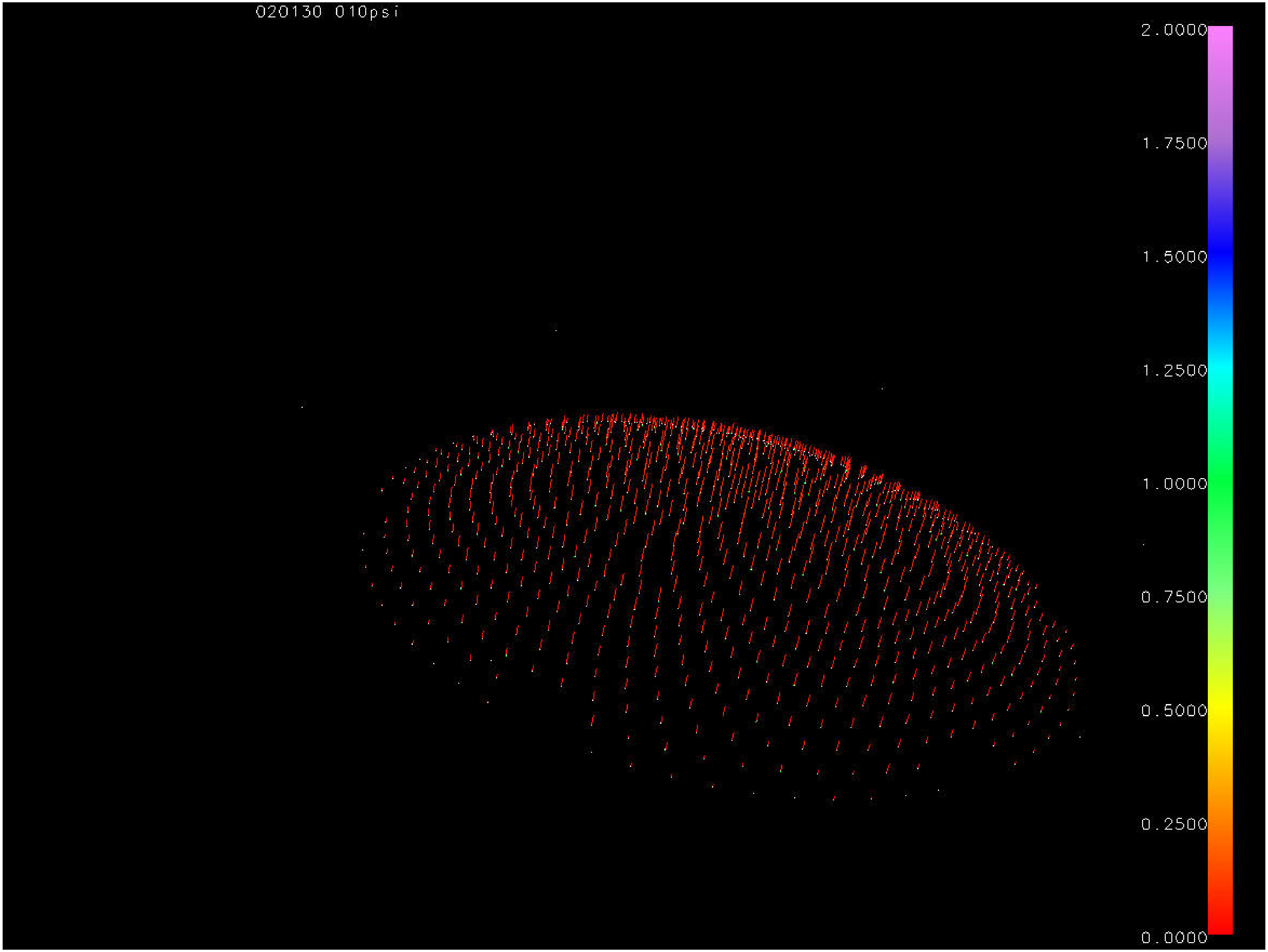
Delta z (mm)

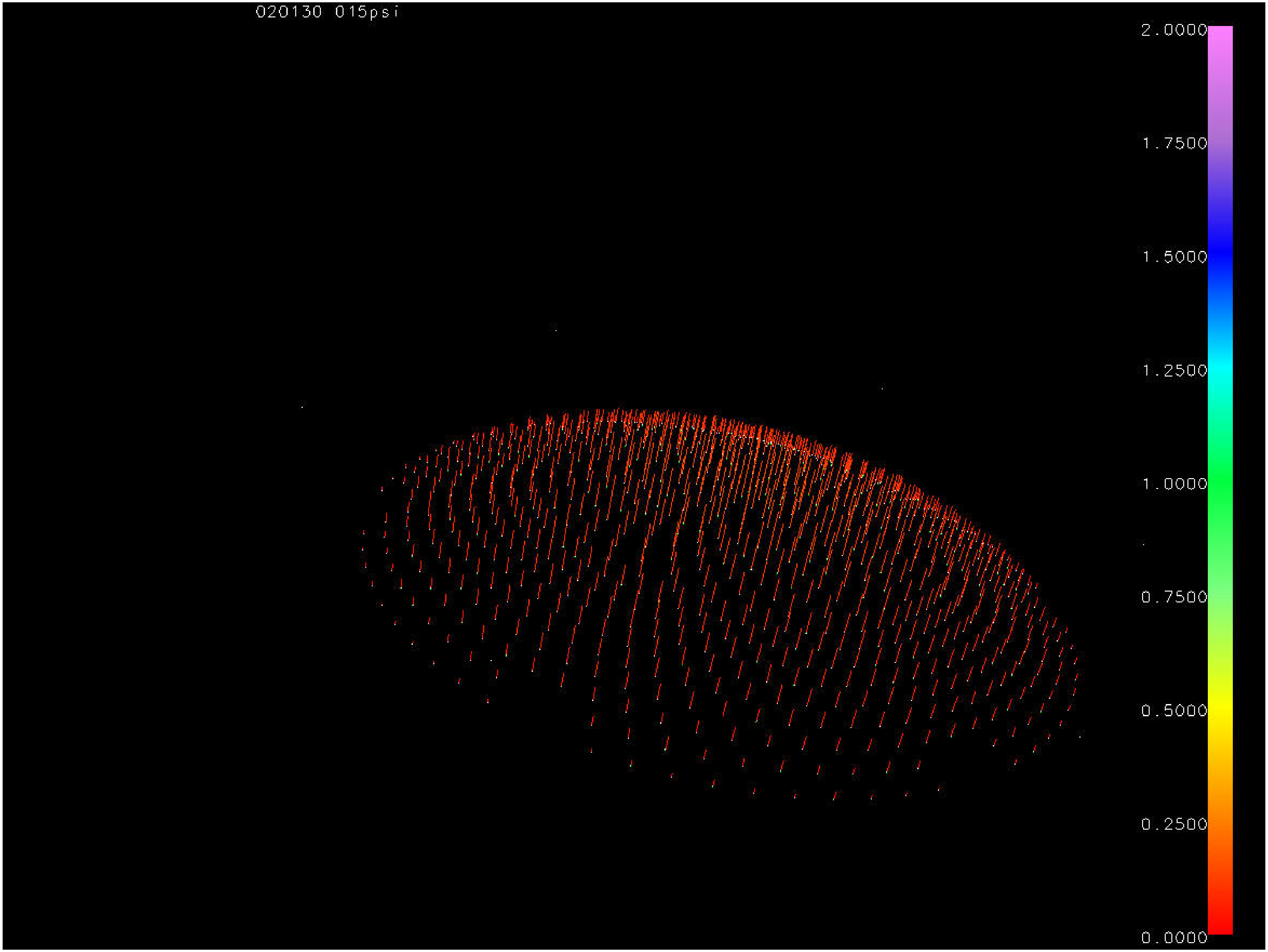
Whisker length =
z(95psi) - z(0psi)



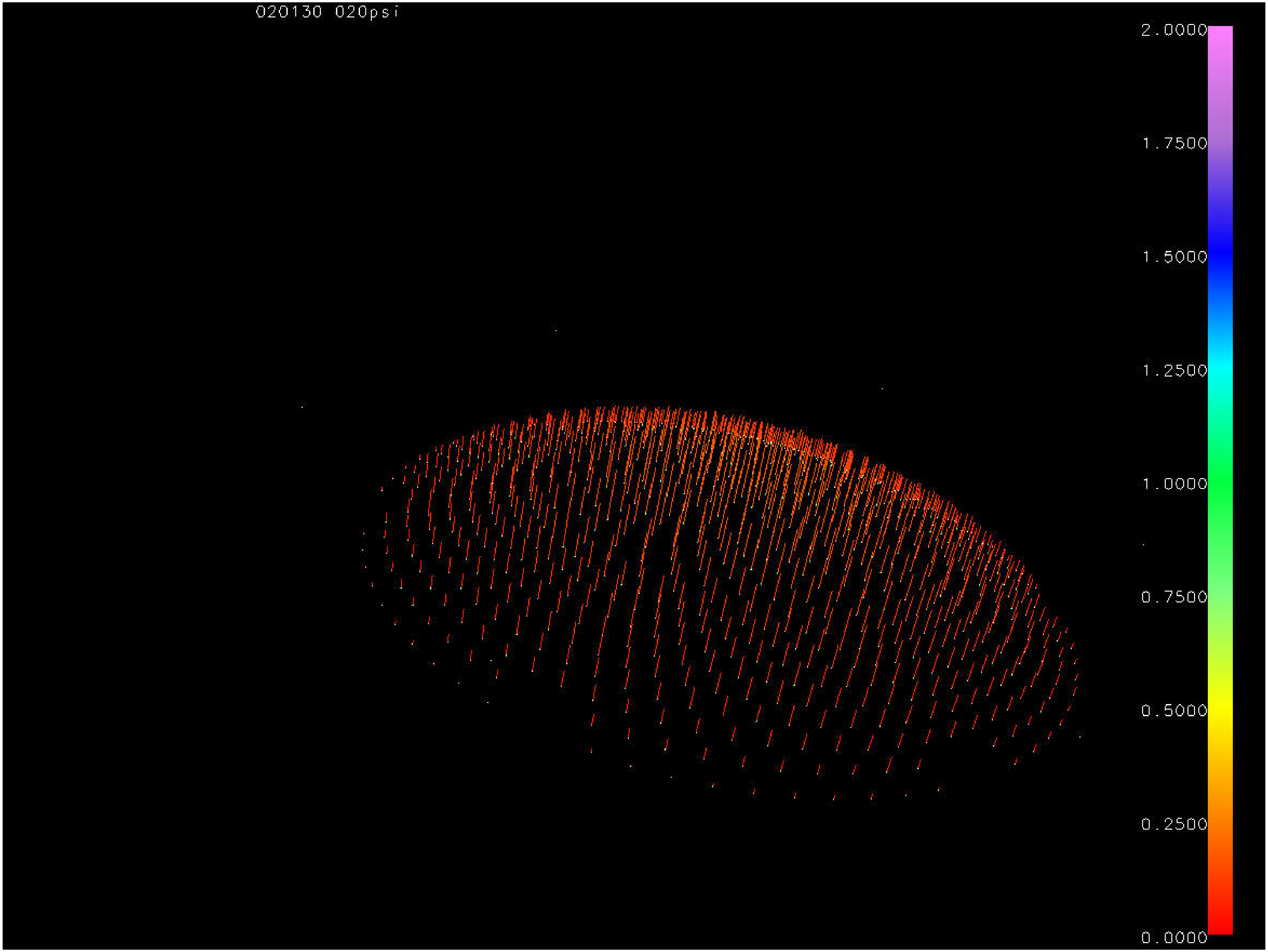
Window 3

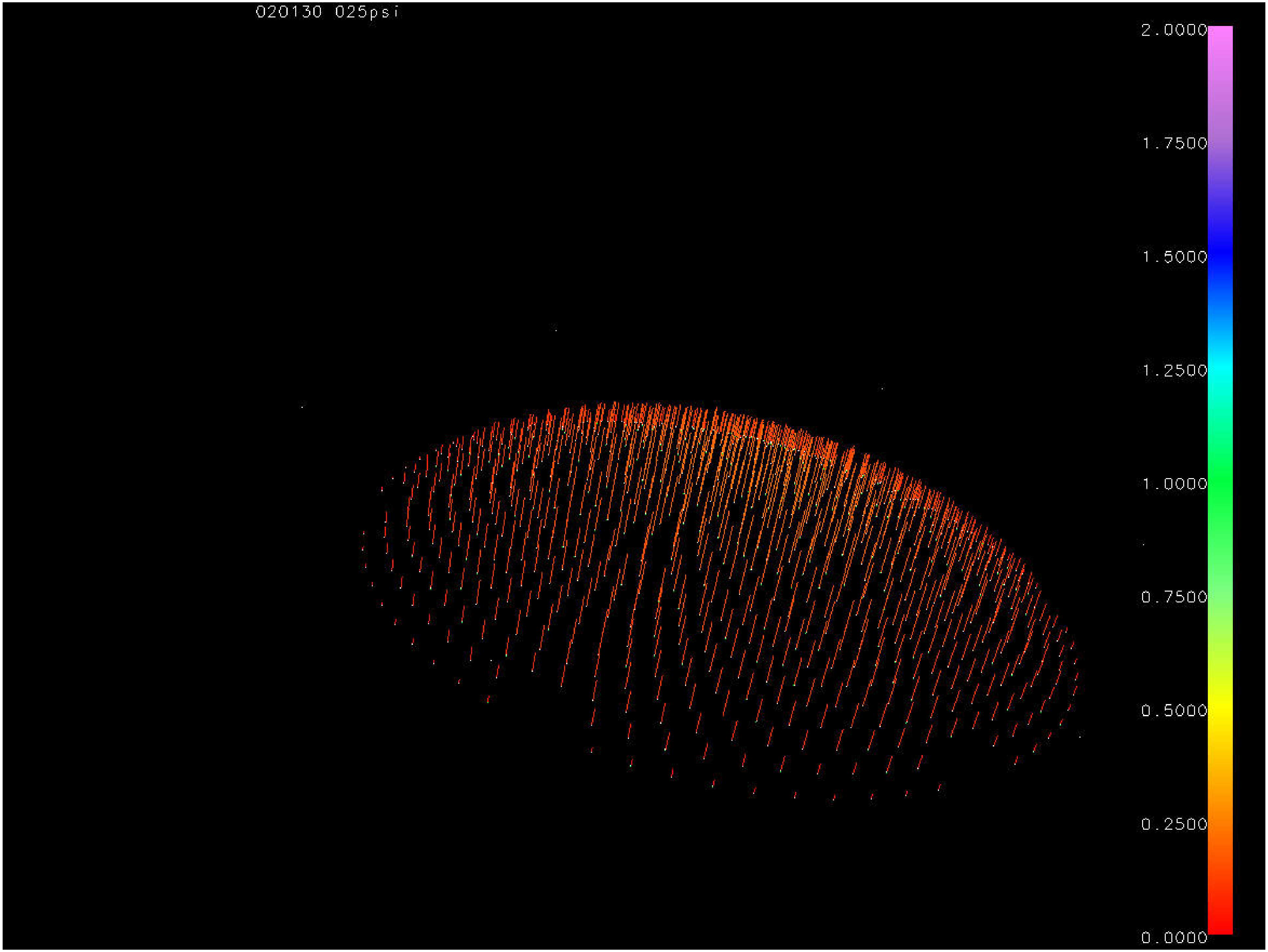
Observe the linear rate of deformation evolve into a nonlinear rate after the Al yields...

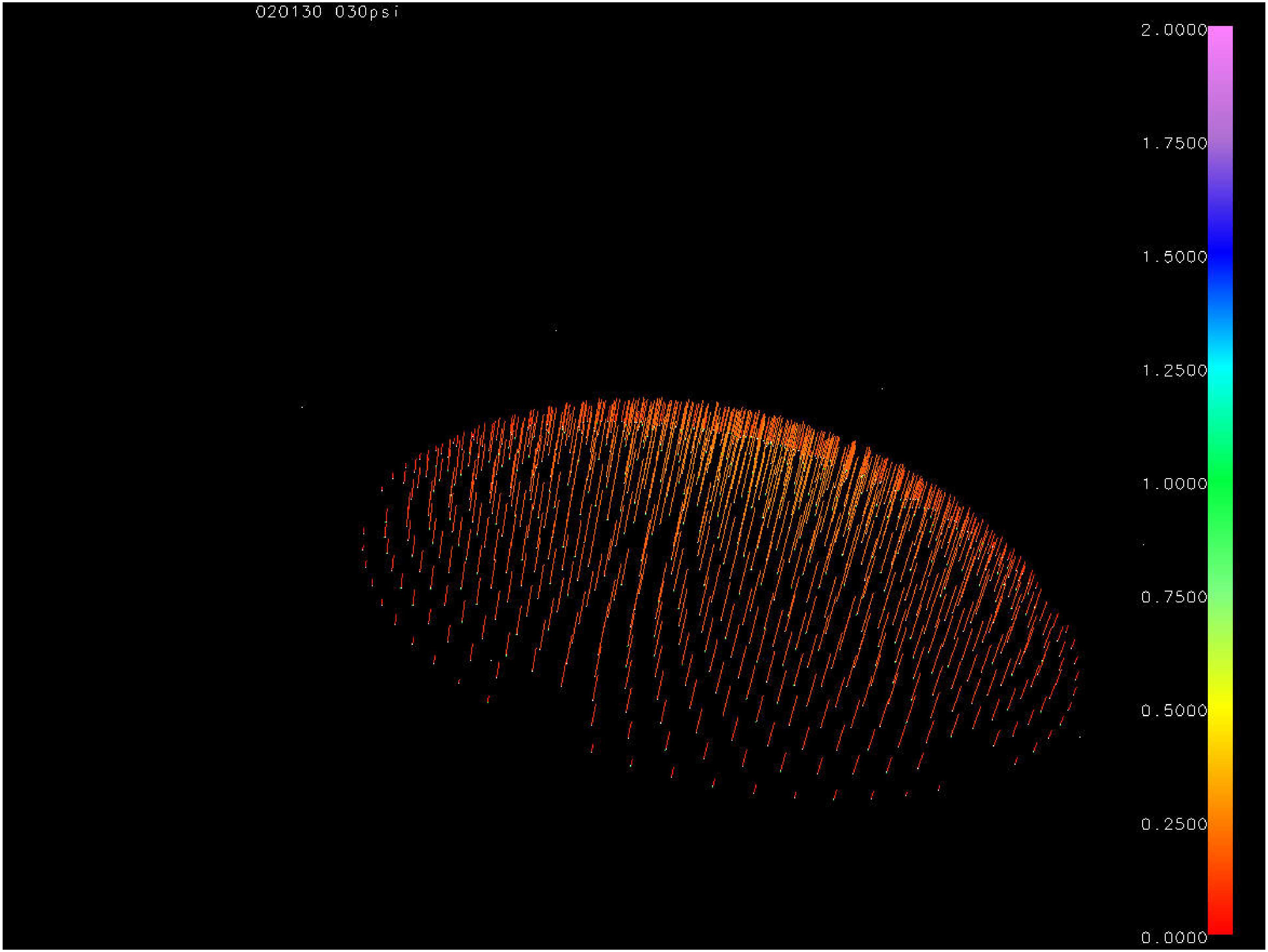

020130 010psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000



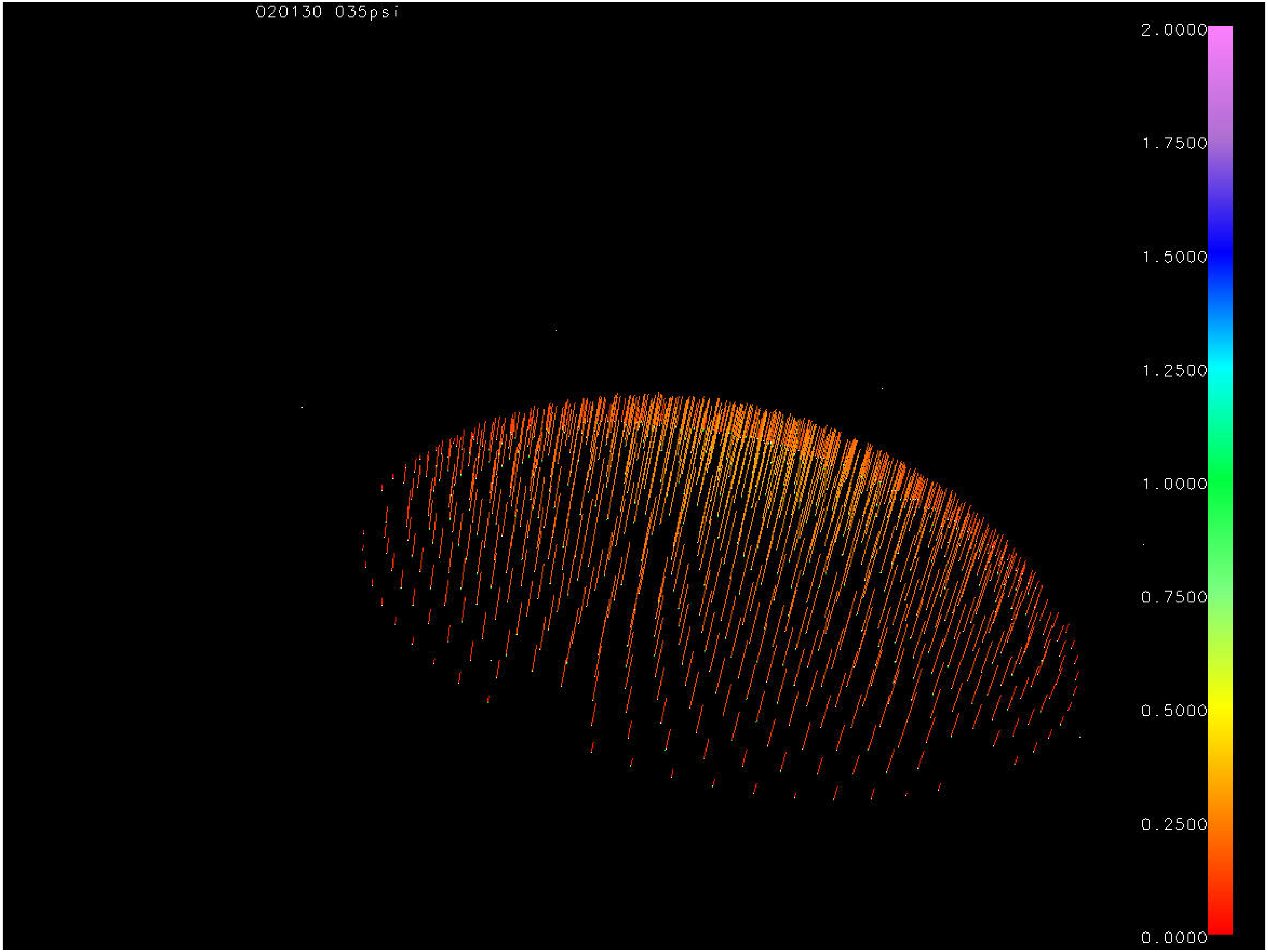
020130 015psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

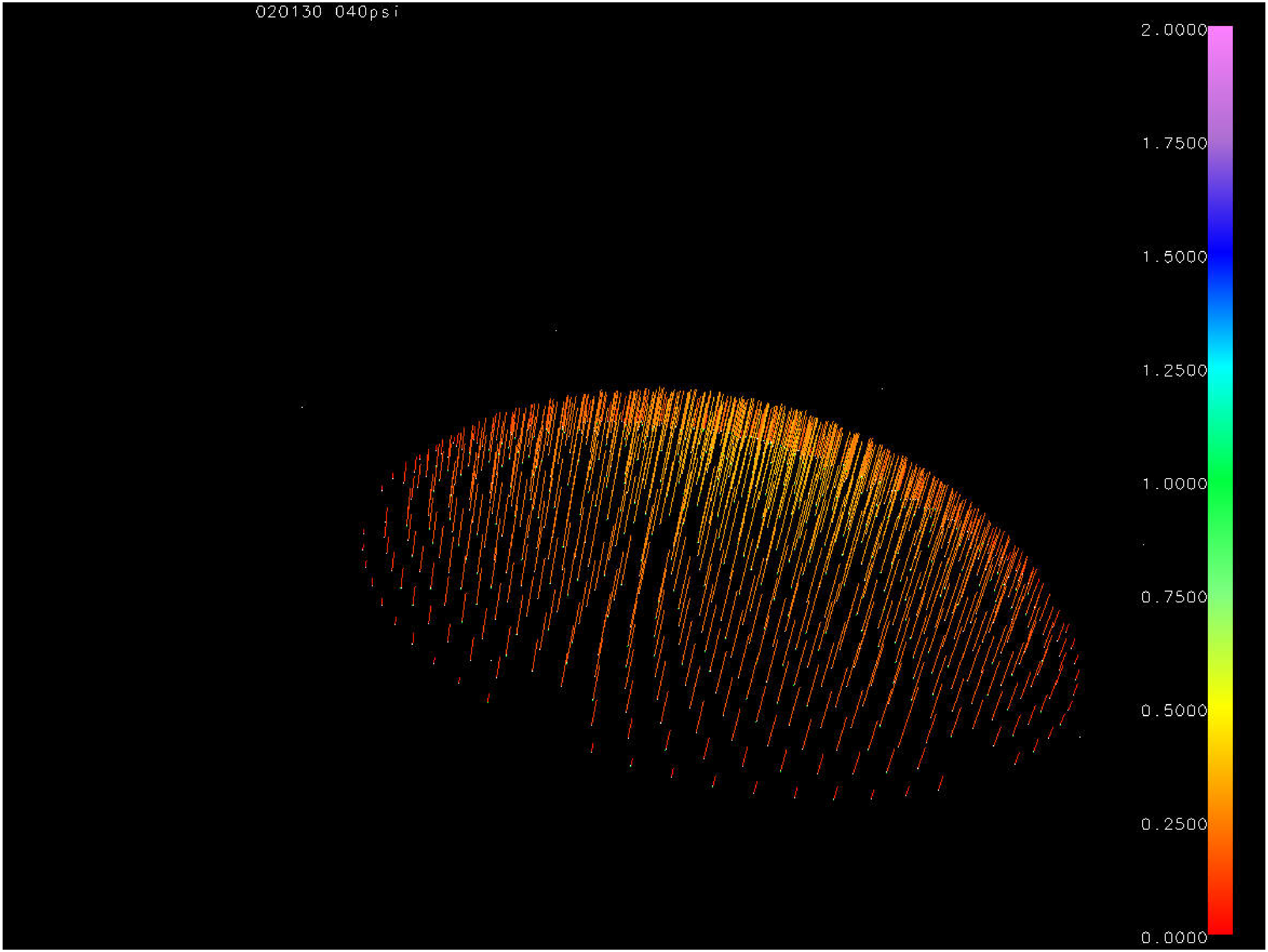

020130 020psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

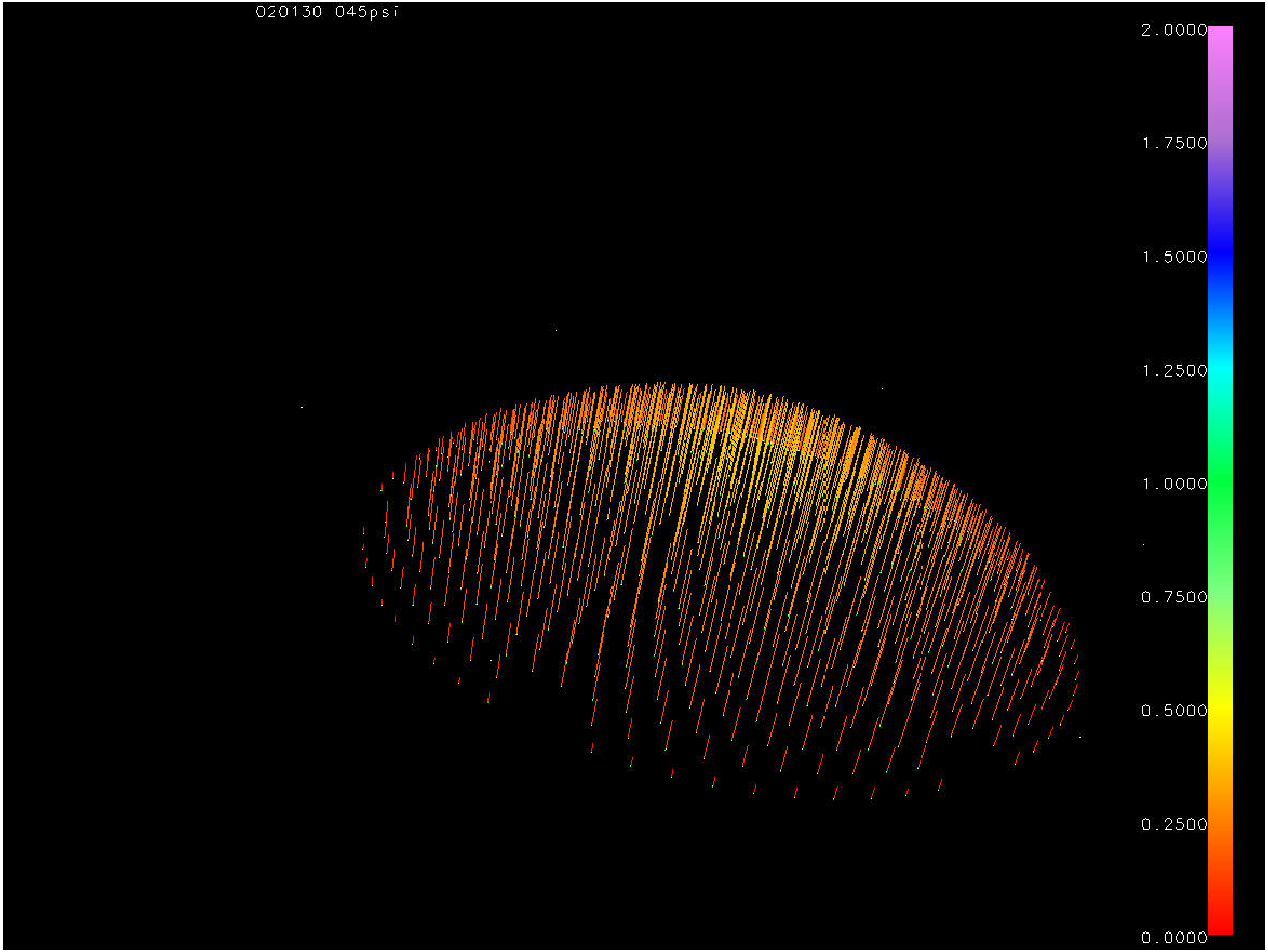

020130 025psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

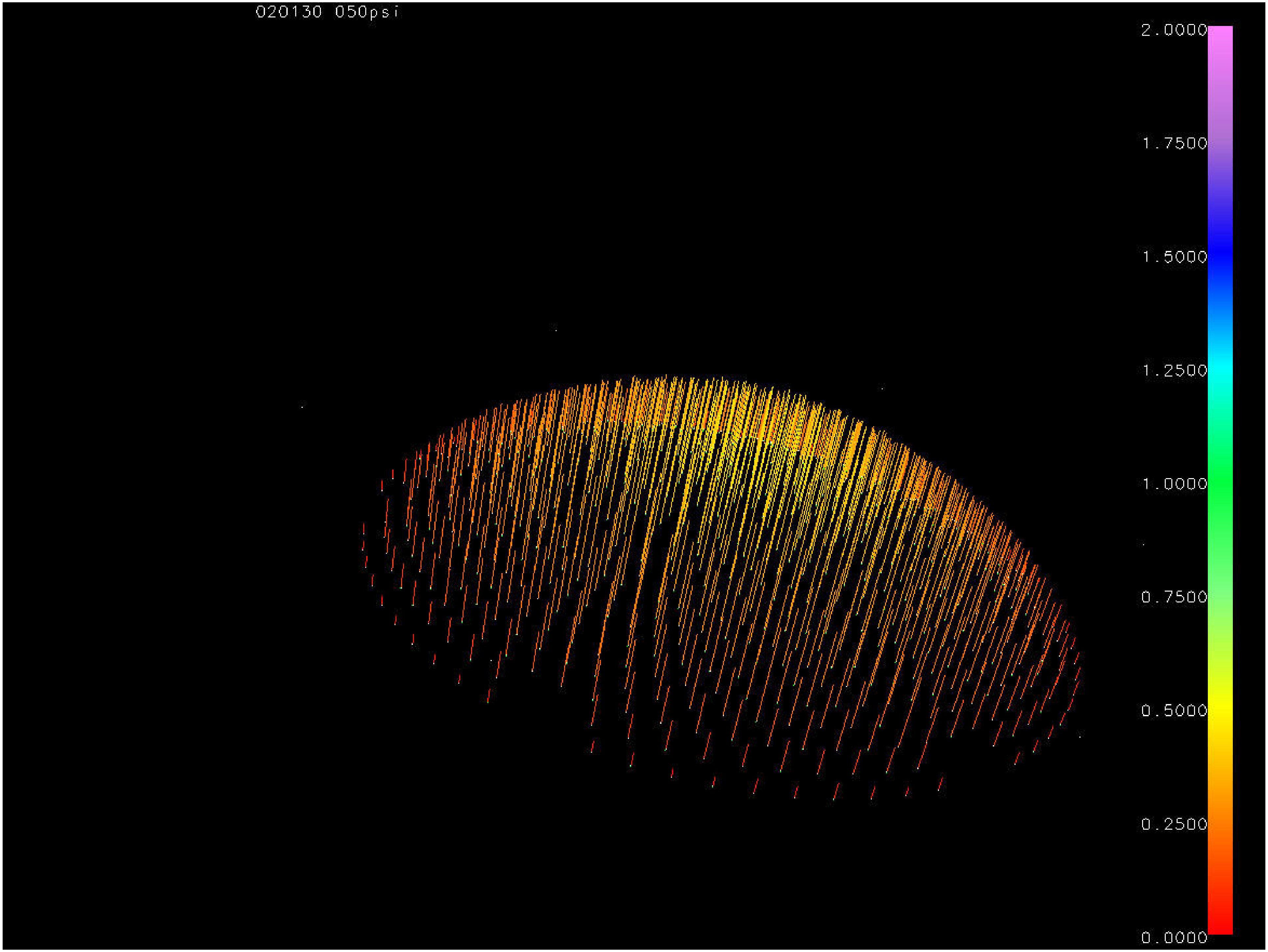


020130 030psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

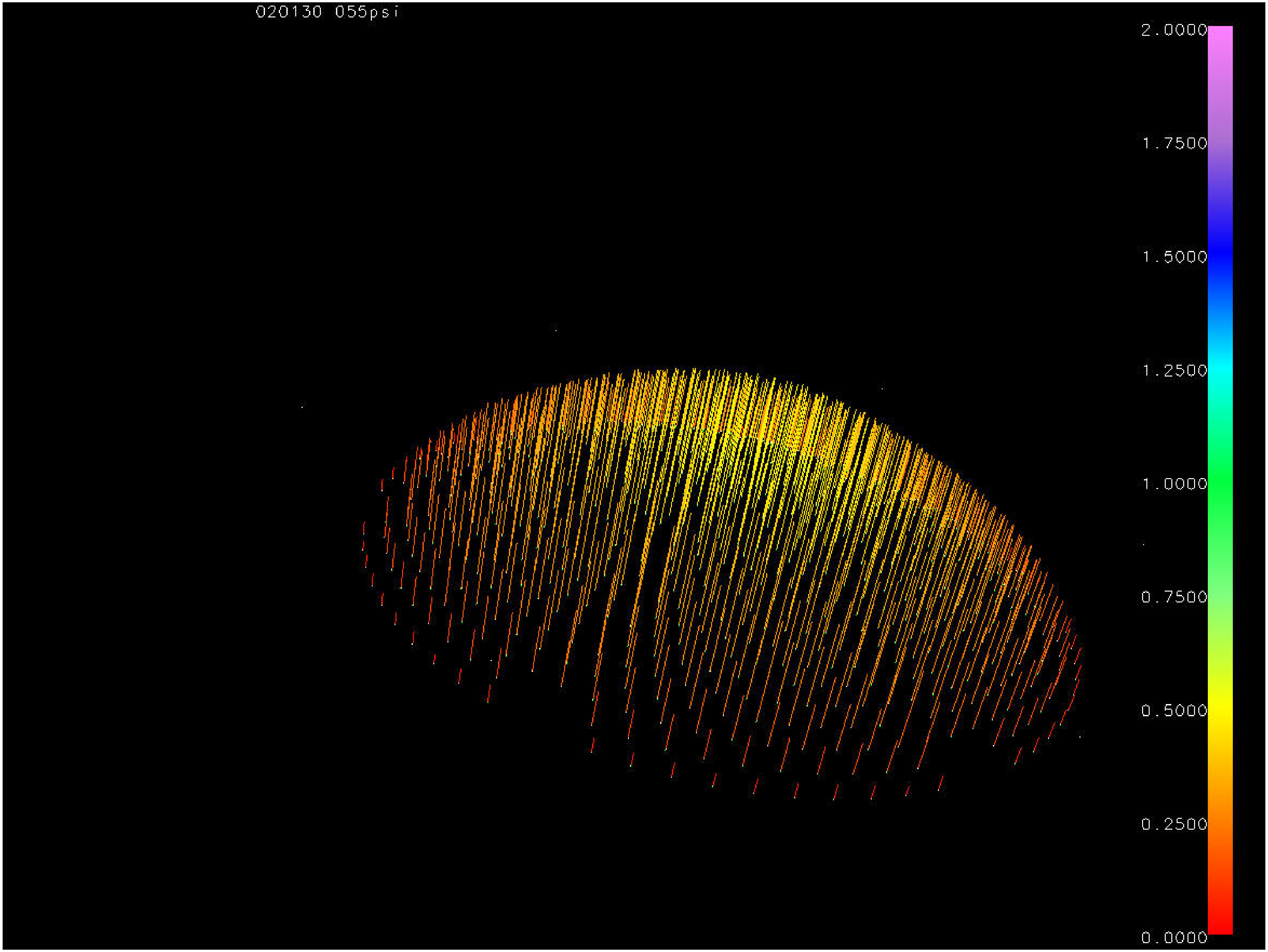

020130 035psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

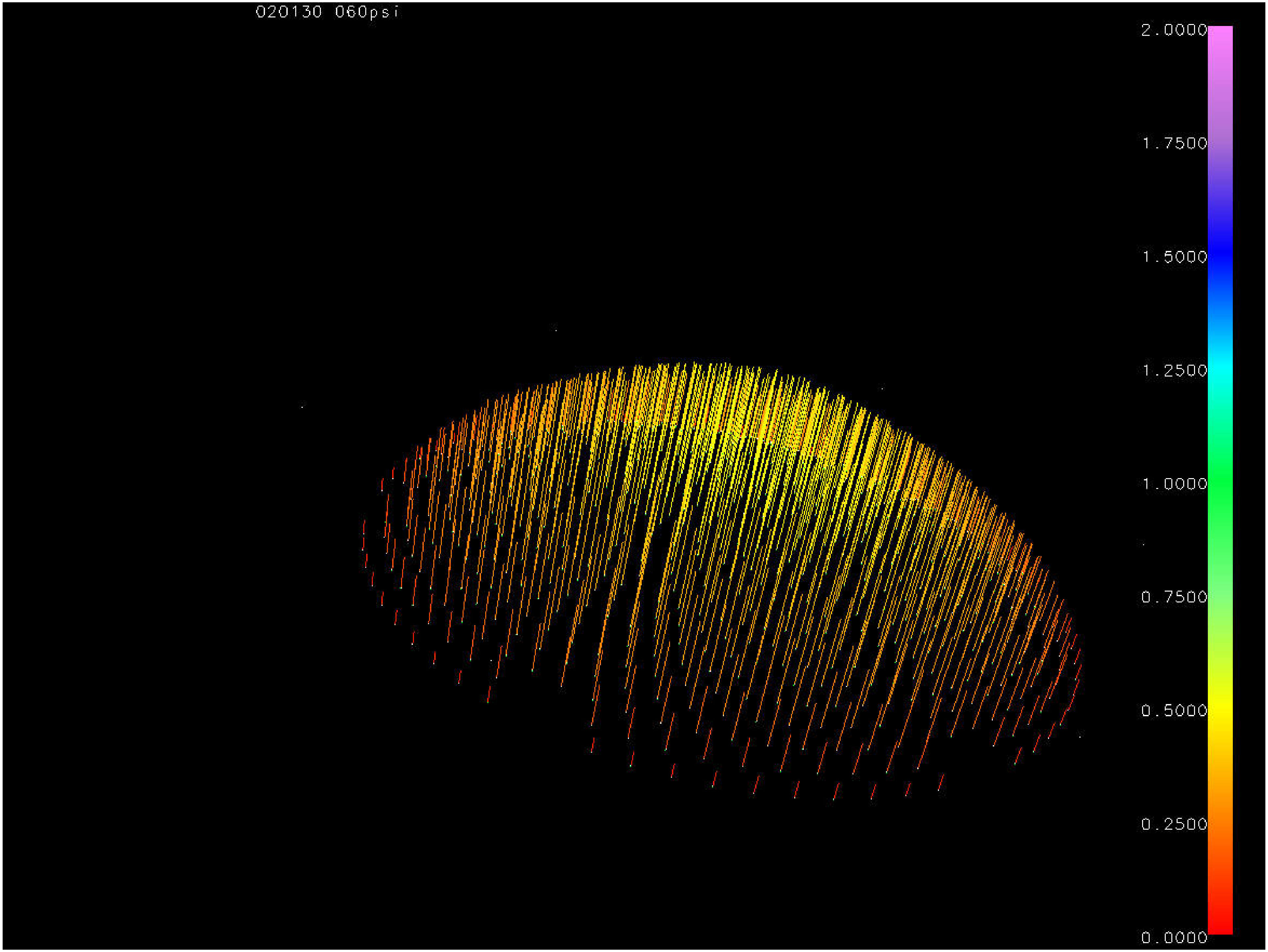

020130 040psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

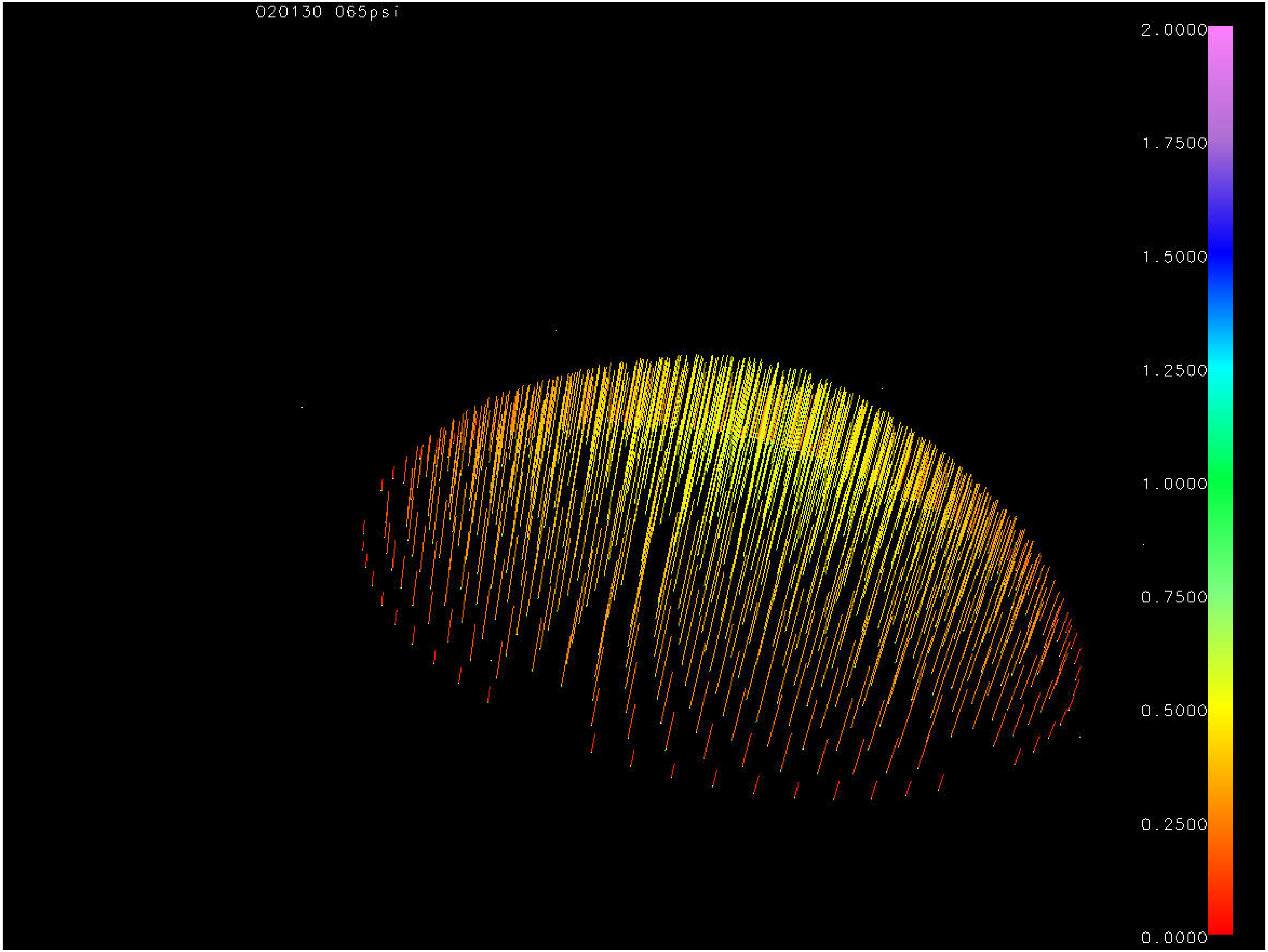

020130 045psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

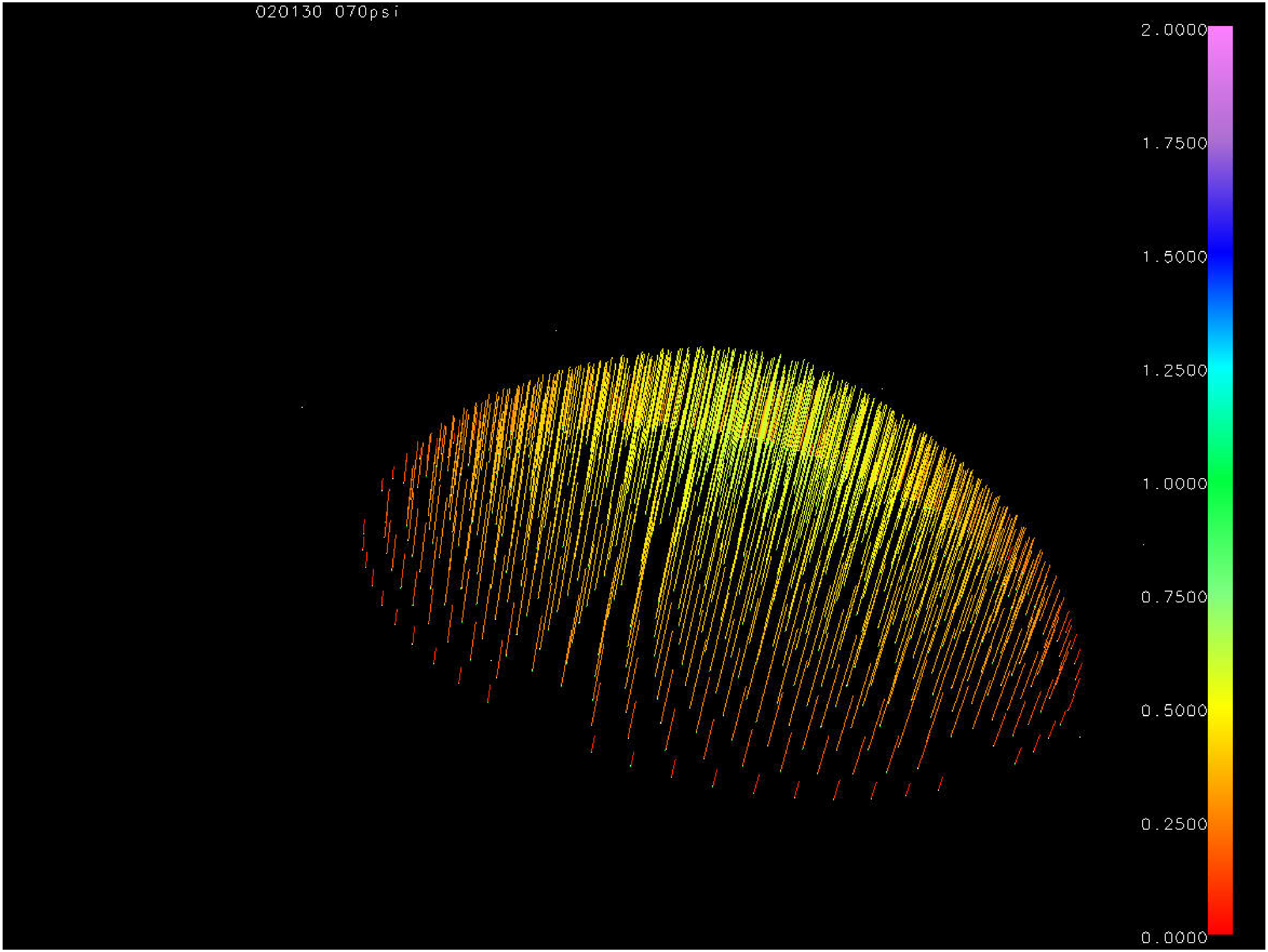


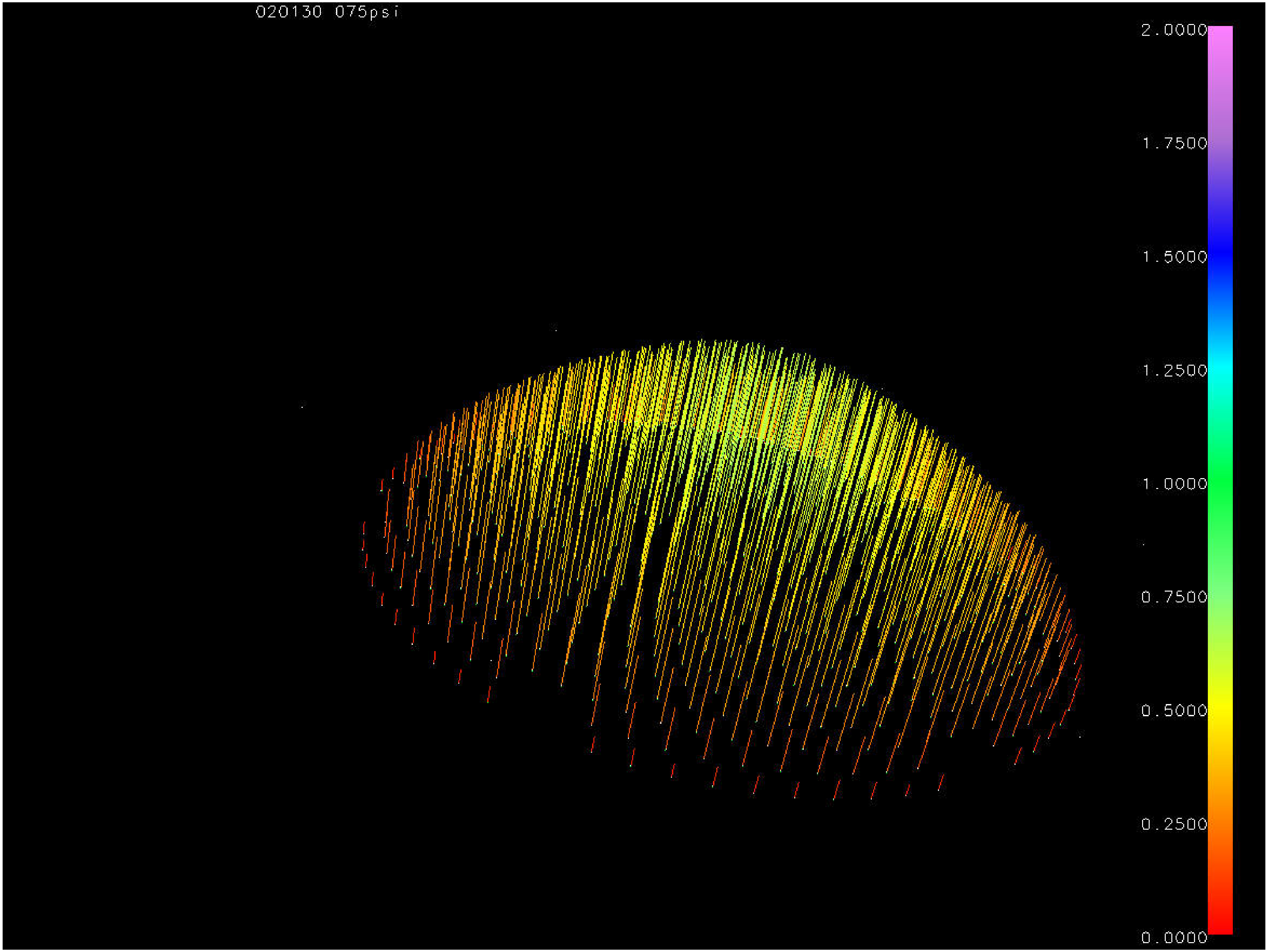
020130 050psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

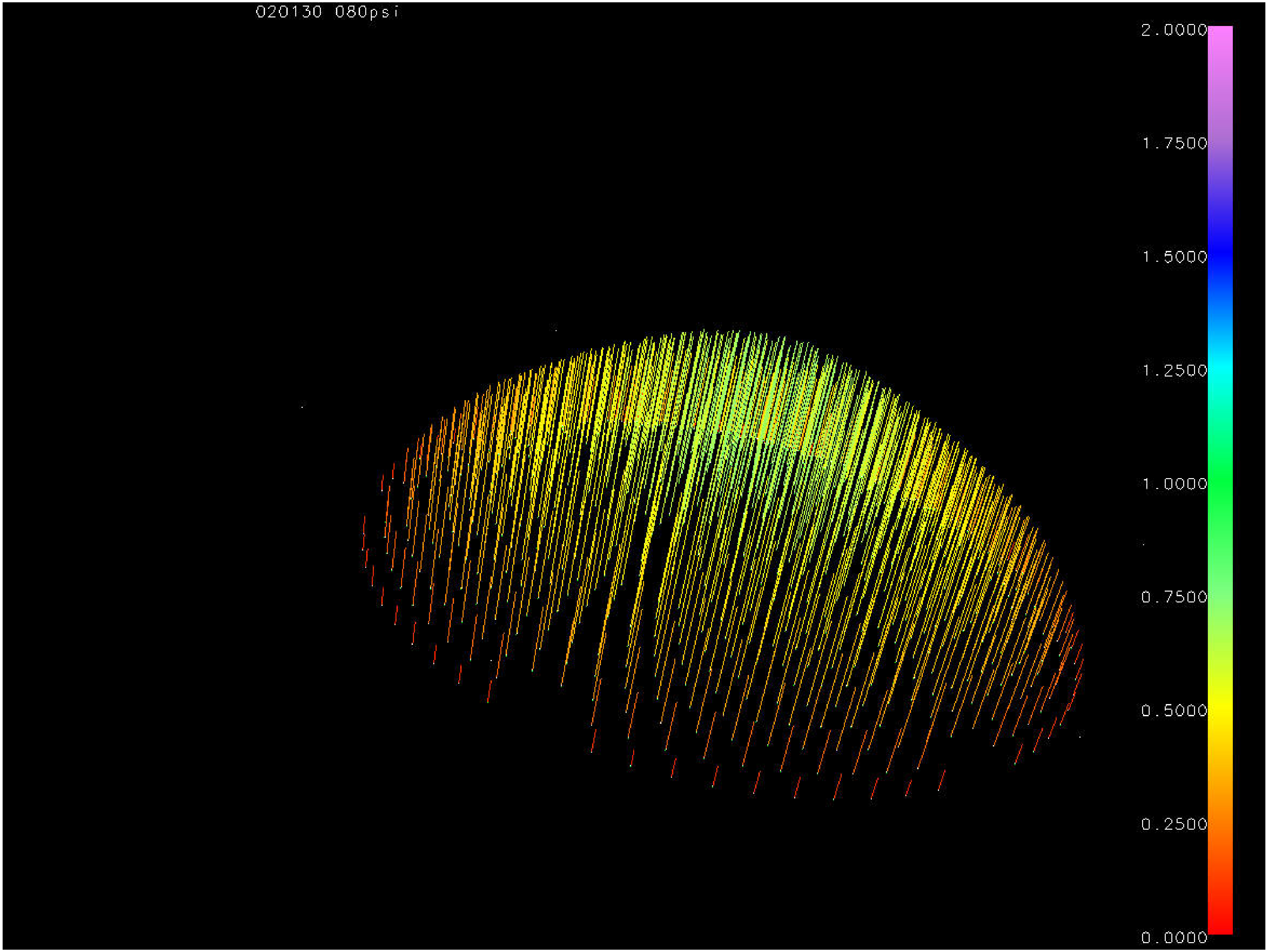

020130 055psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

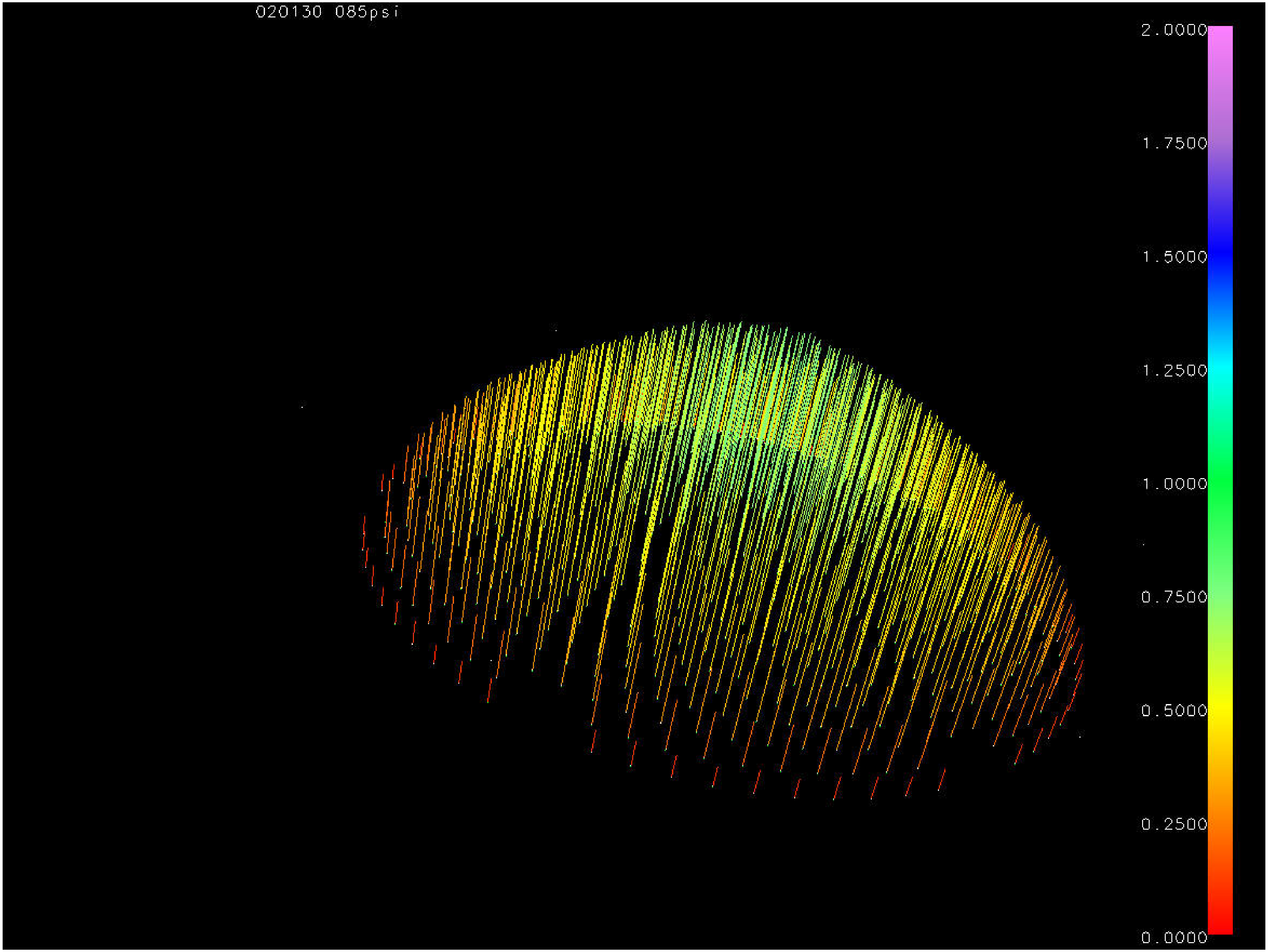

020130 060psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

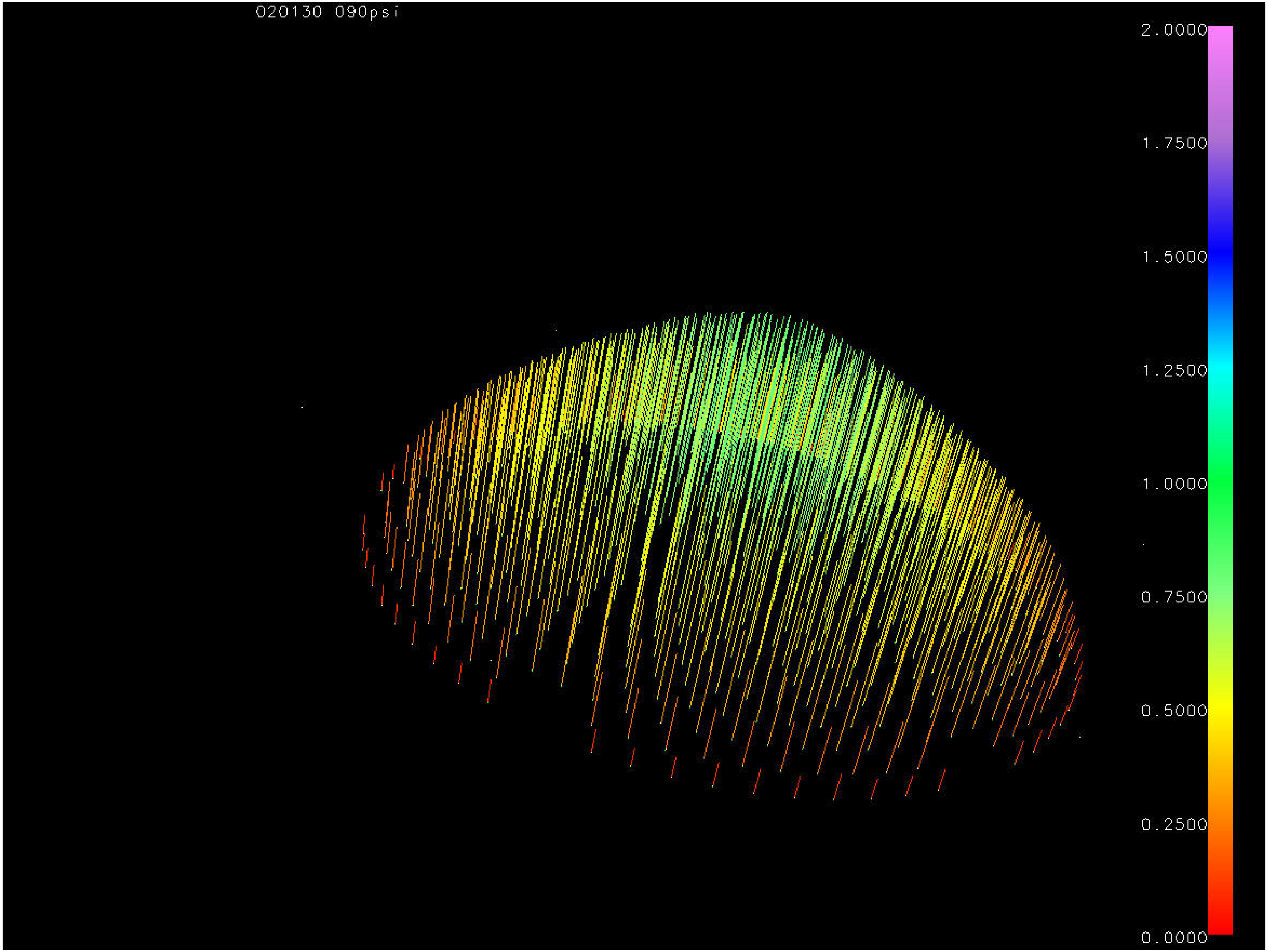

020130 065psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

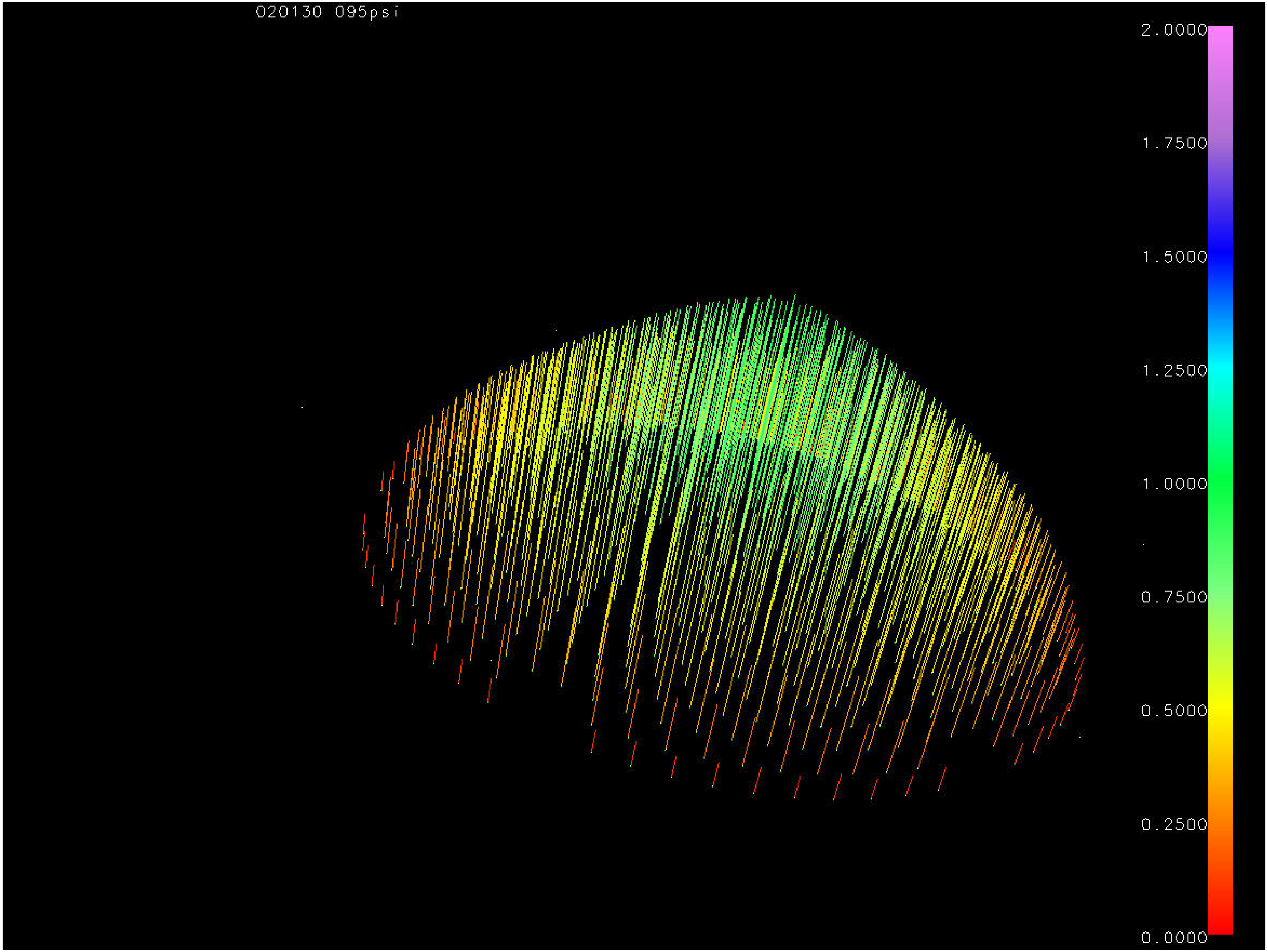

020130 070psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000


020130 075psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

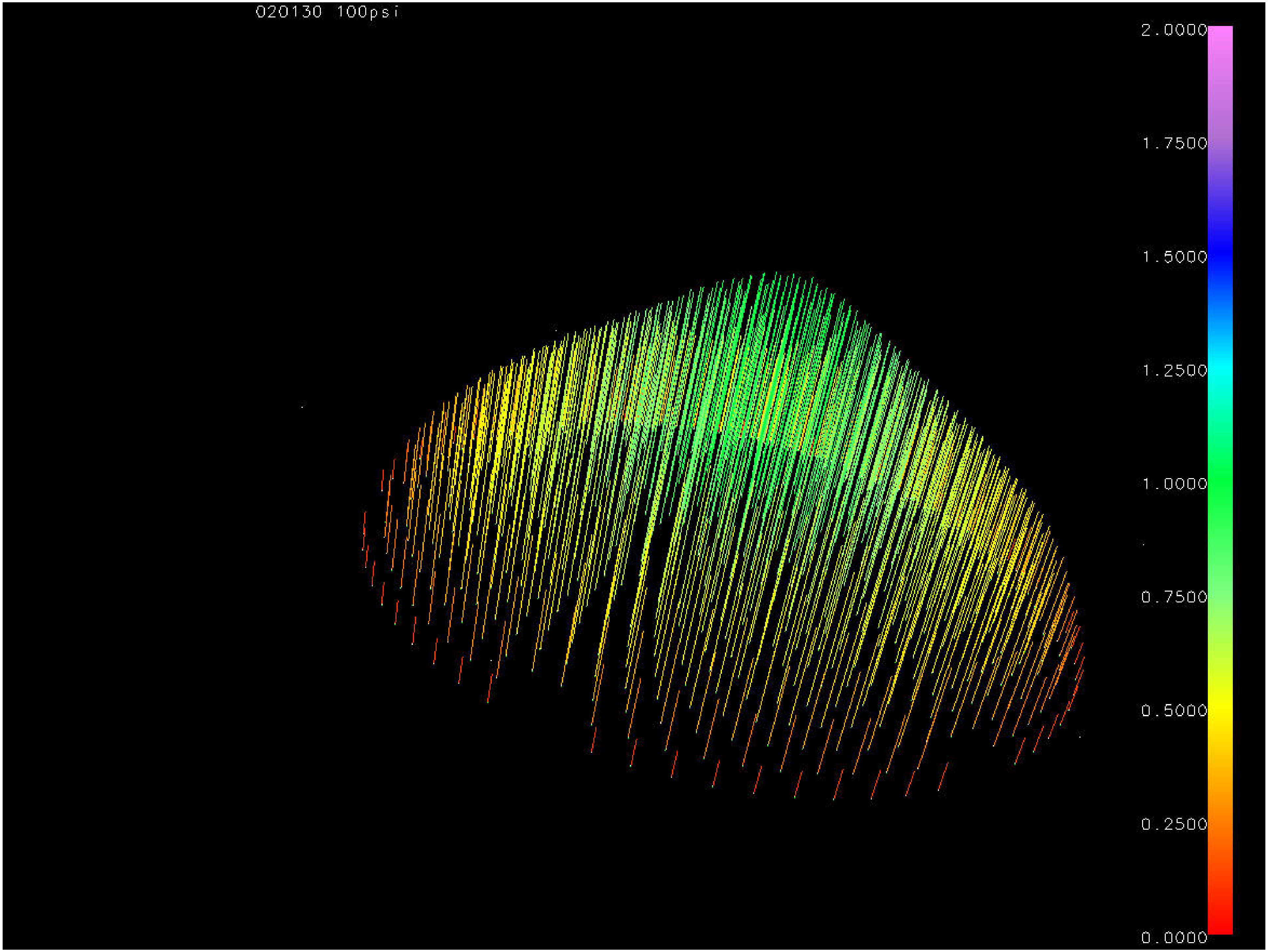

020130 080psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

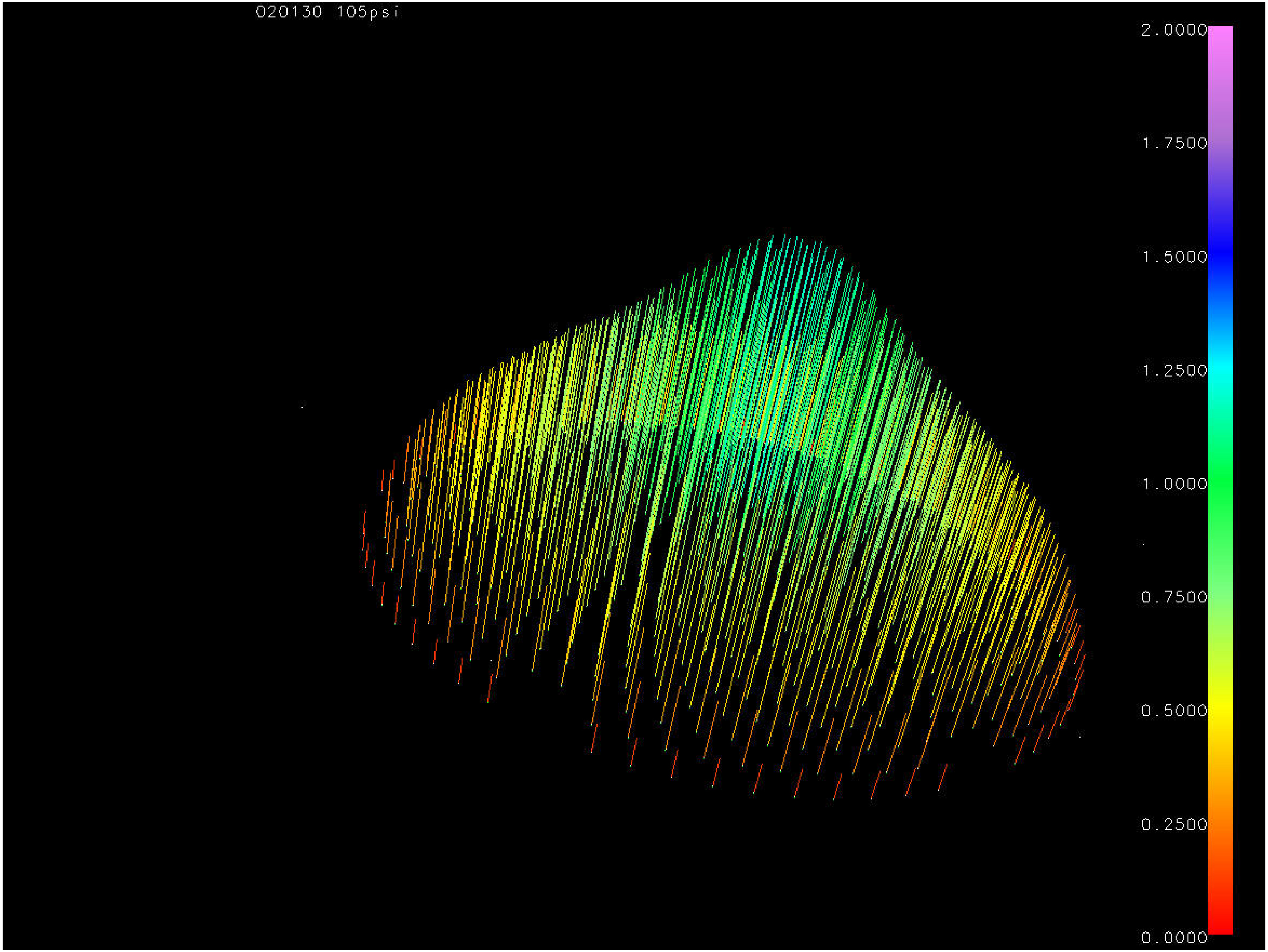

020130 085psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

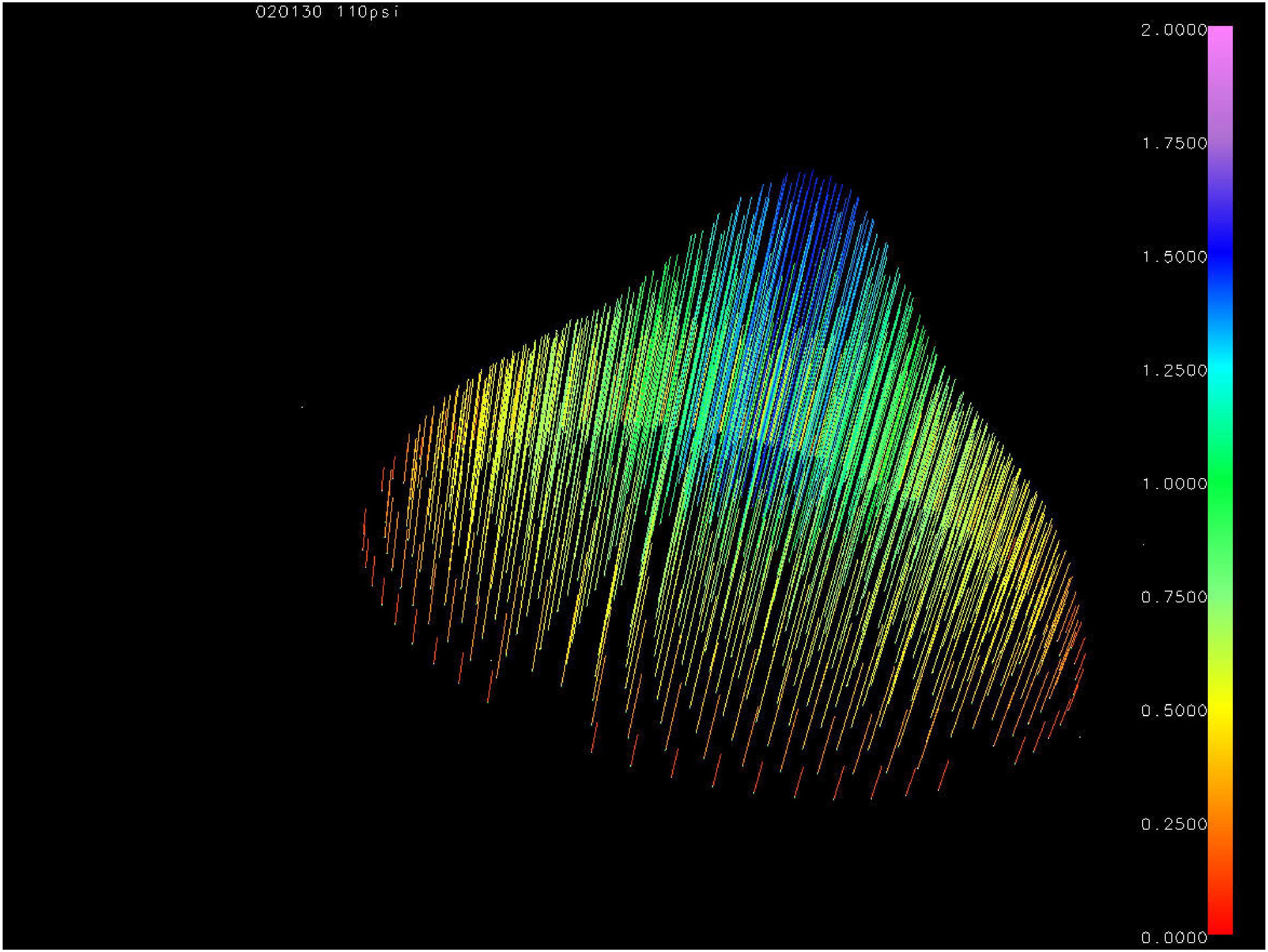

020130 090psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

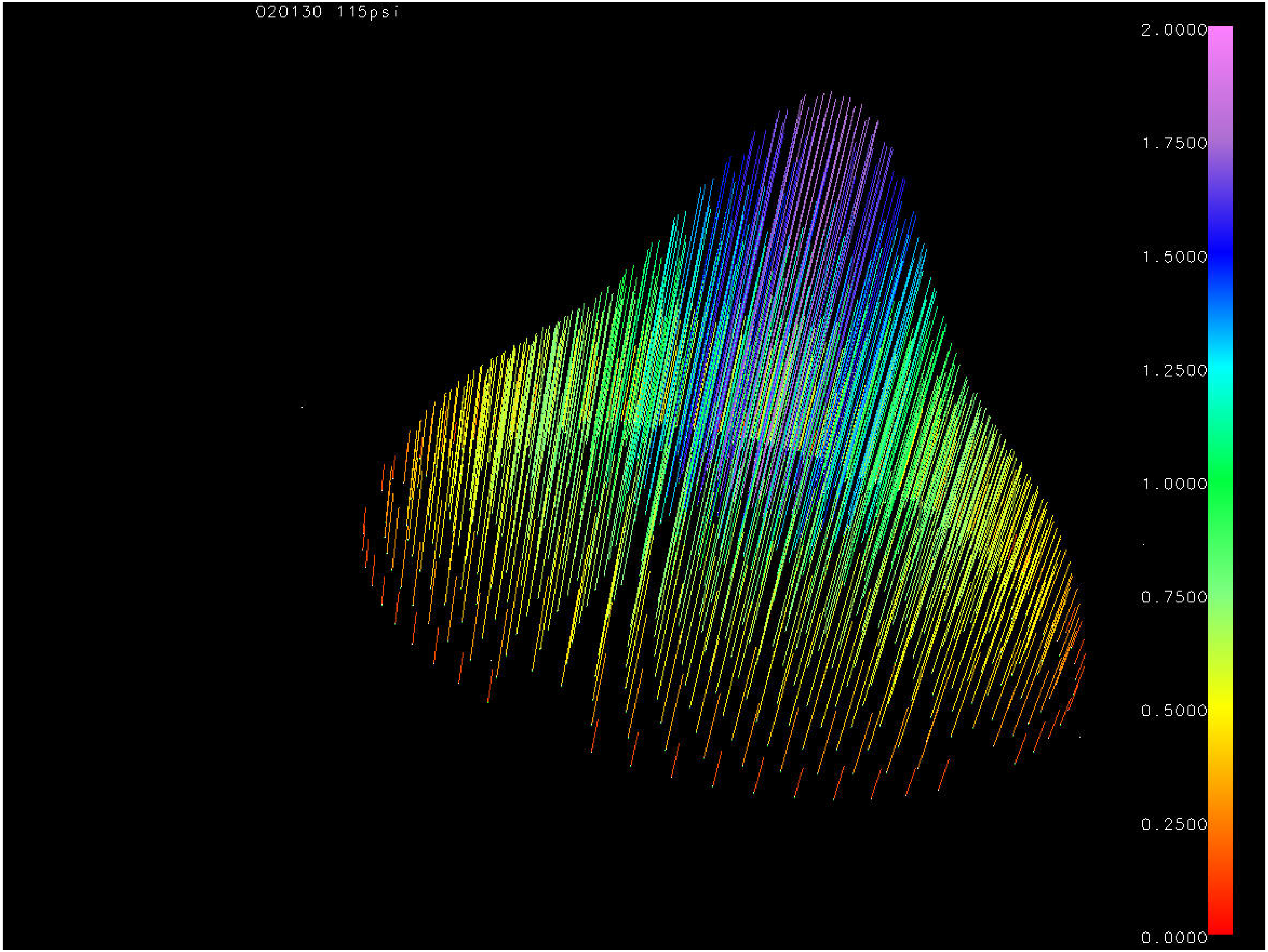


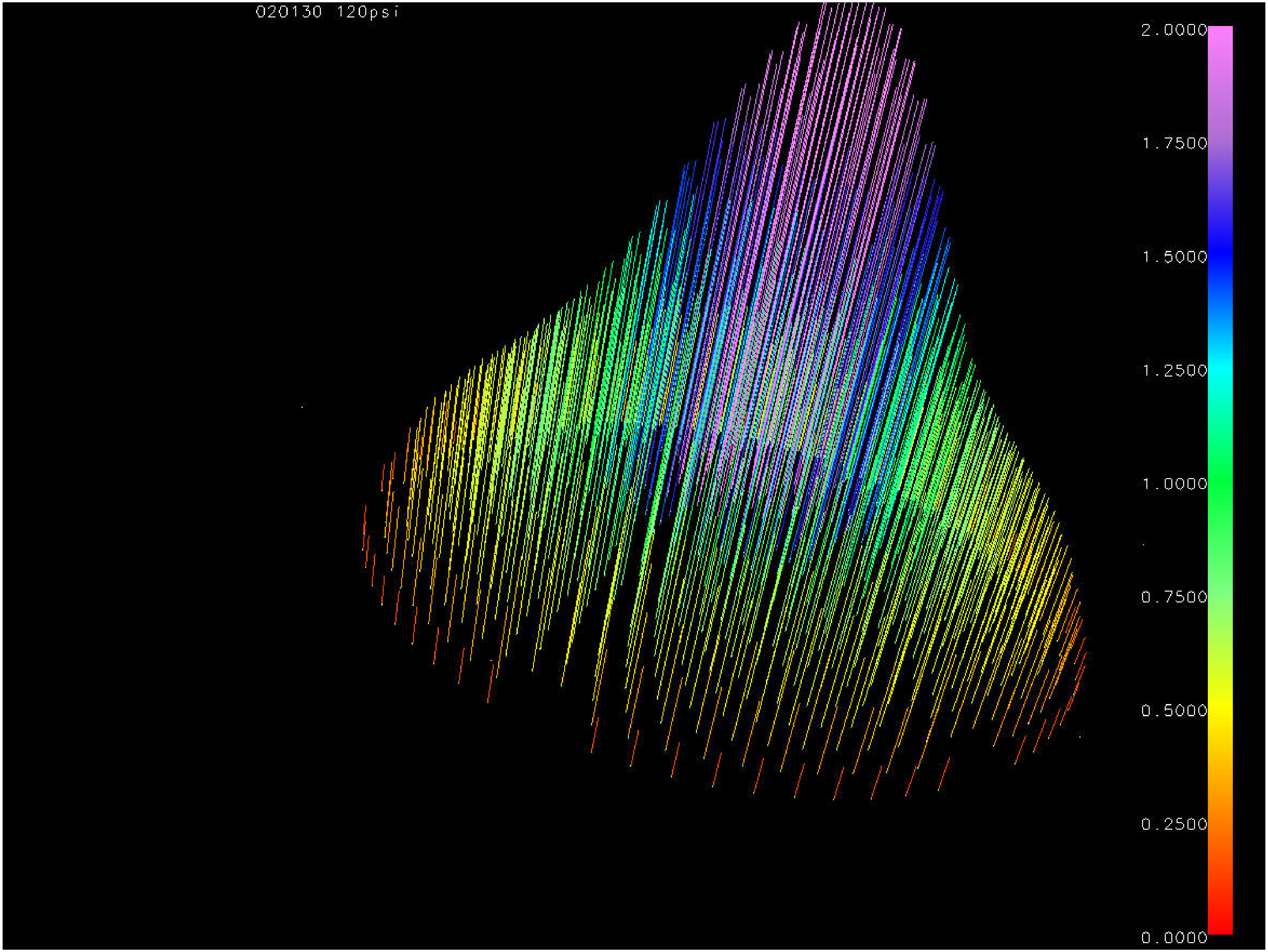
020130 095psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000


020130 100psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000


020130 105psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000


020130 110psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

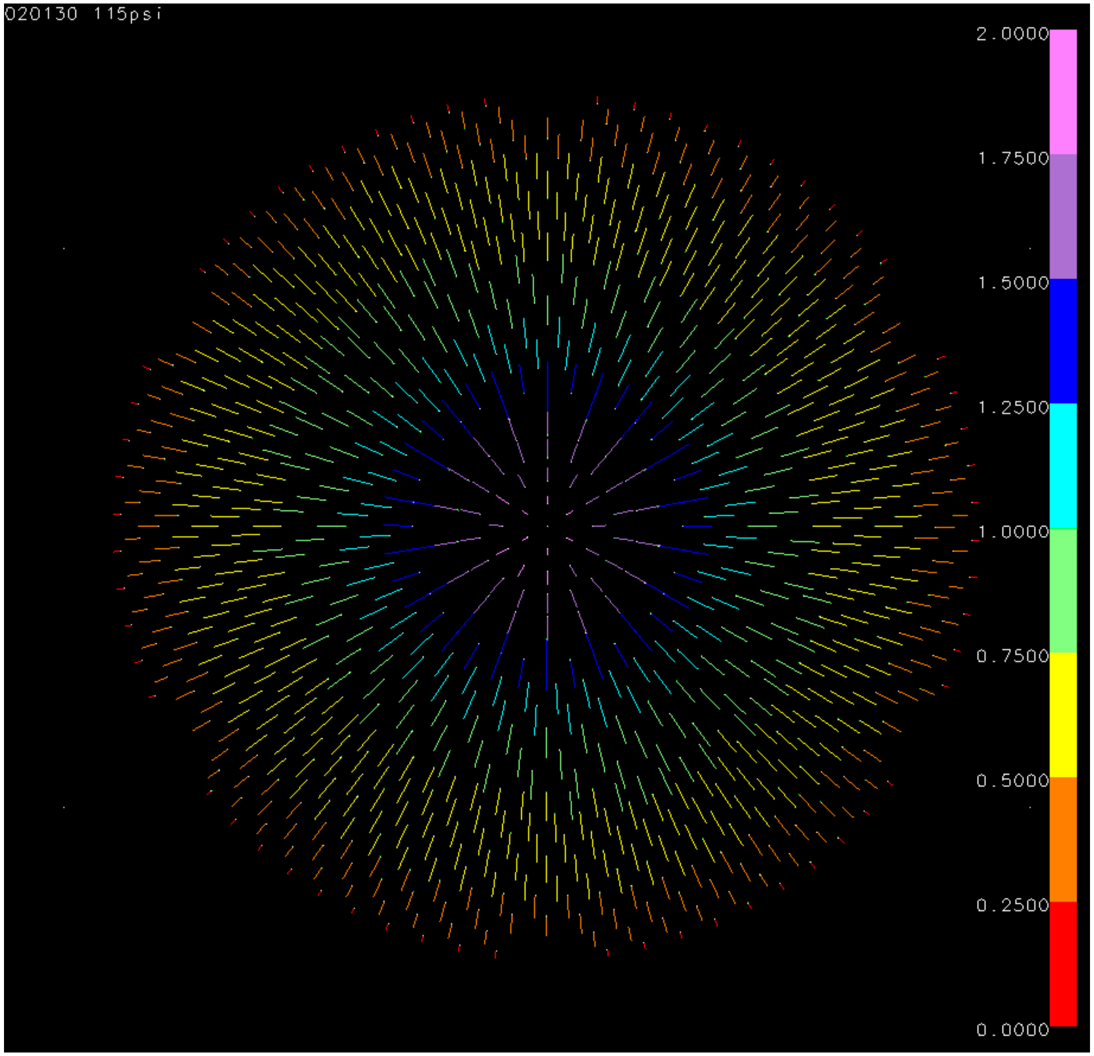

020130 115psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000


020130 120psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000

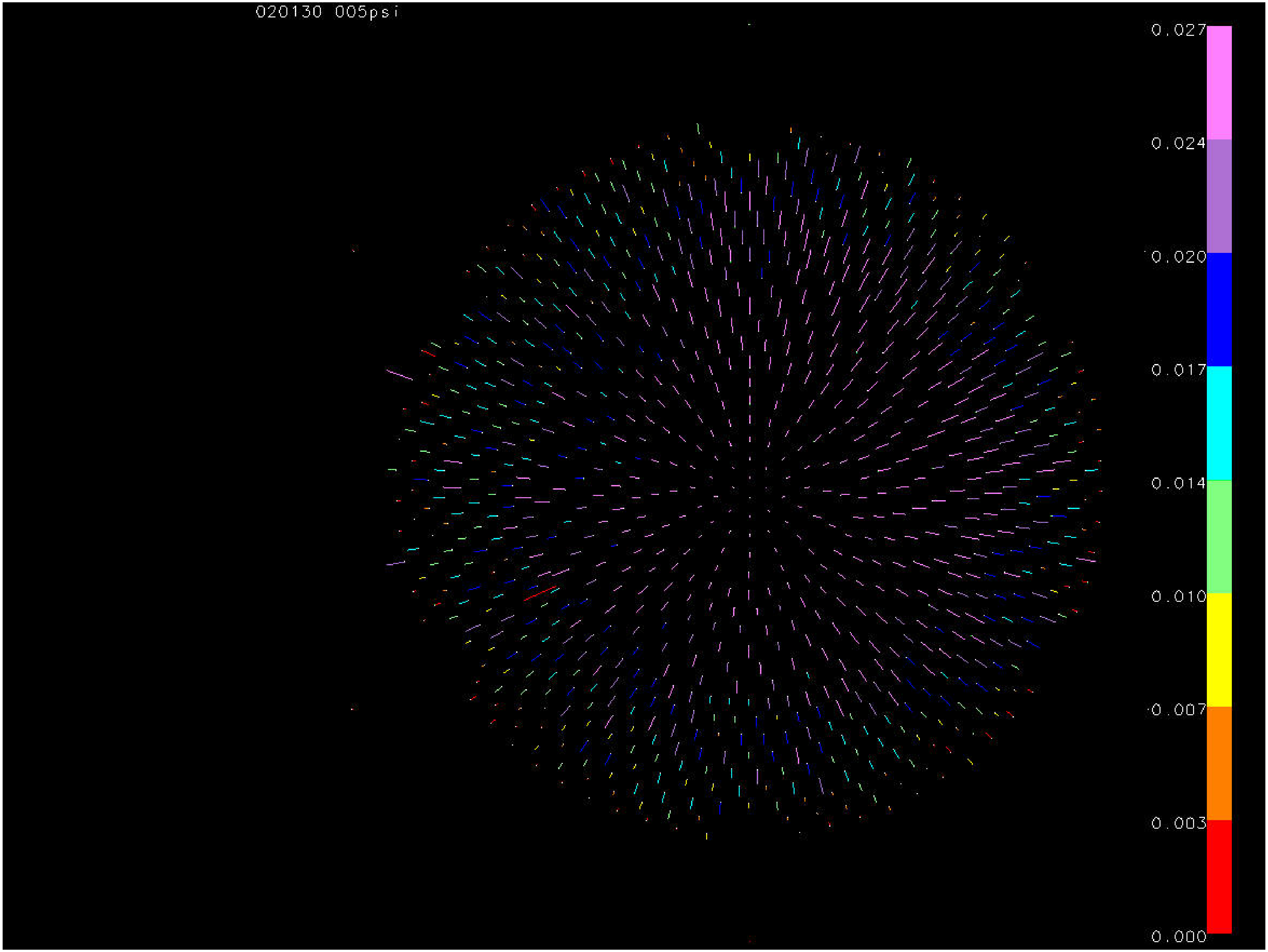
Symmetry

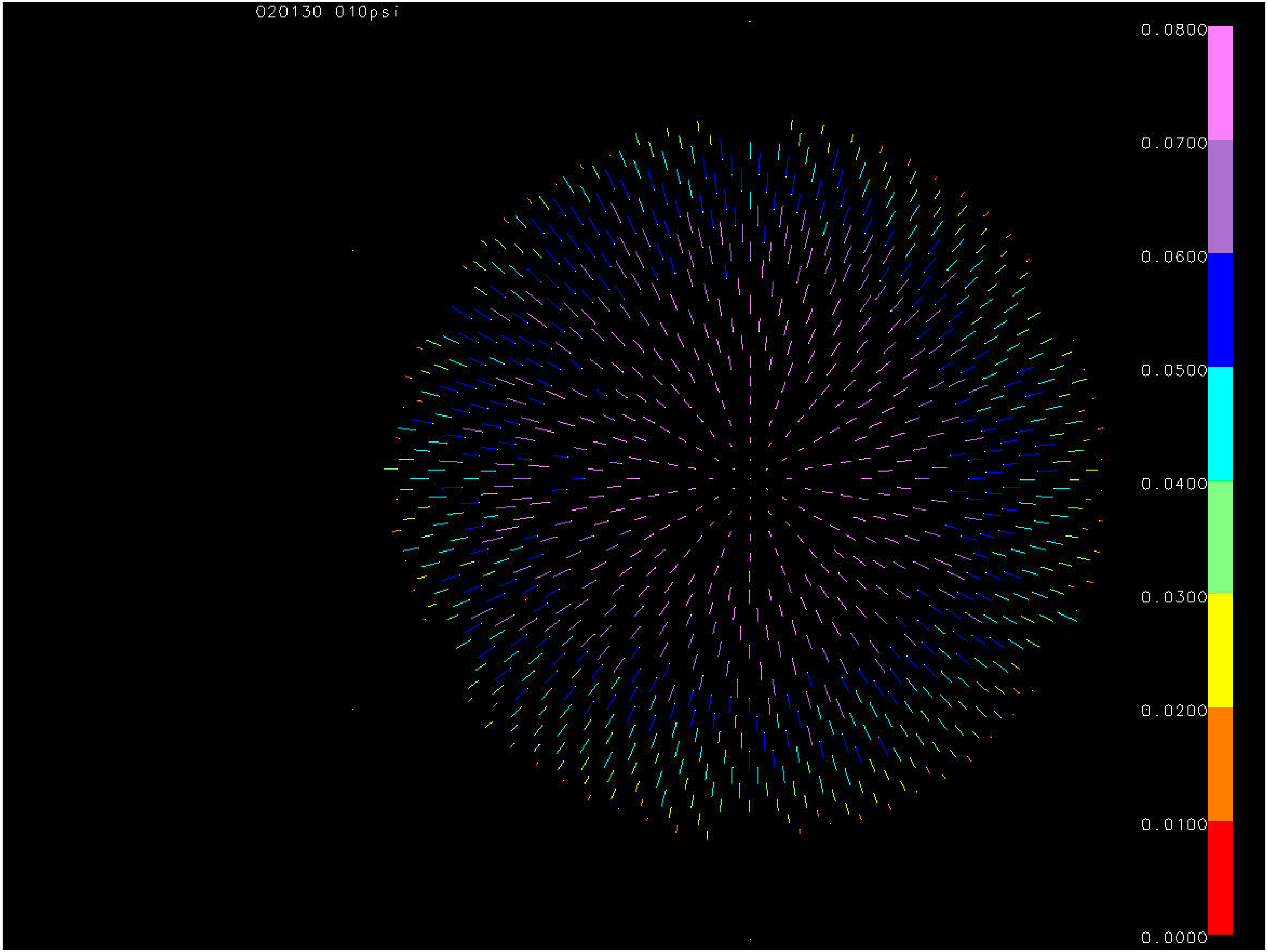
By plotting the *change* from initial shape, any asymmetry due to pattern or window eccentricity is removed.

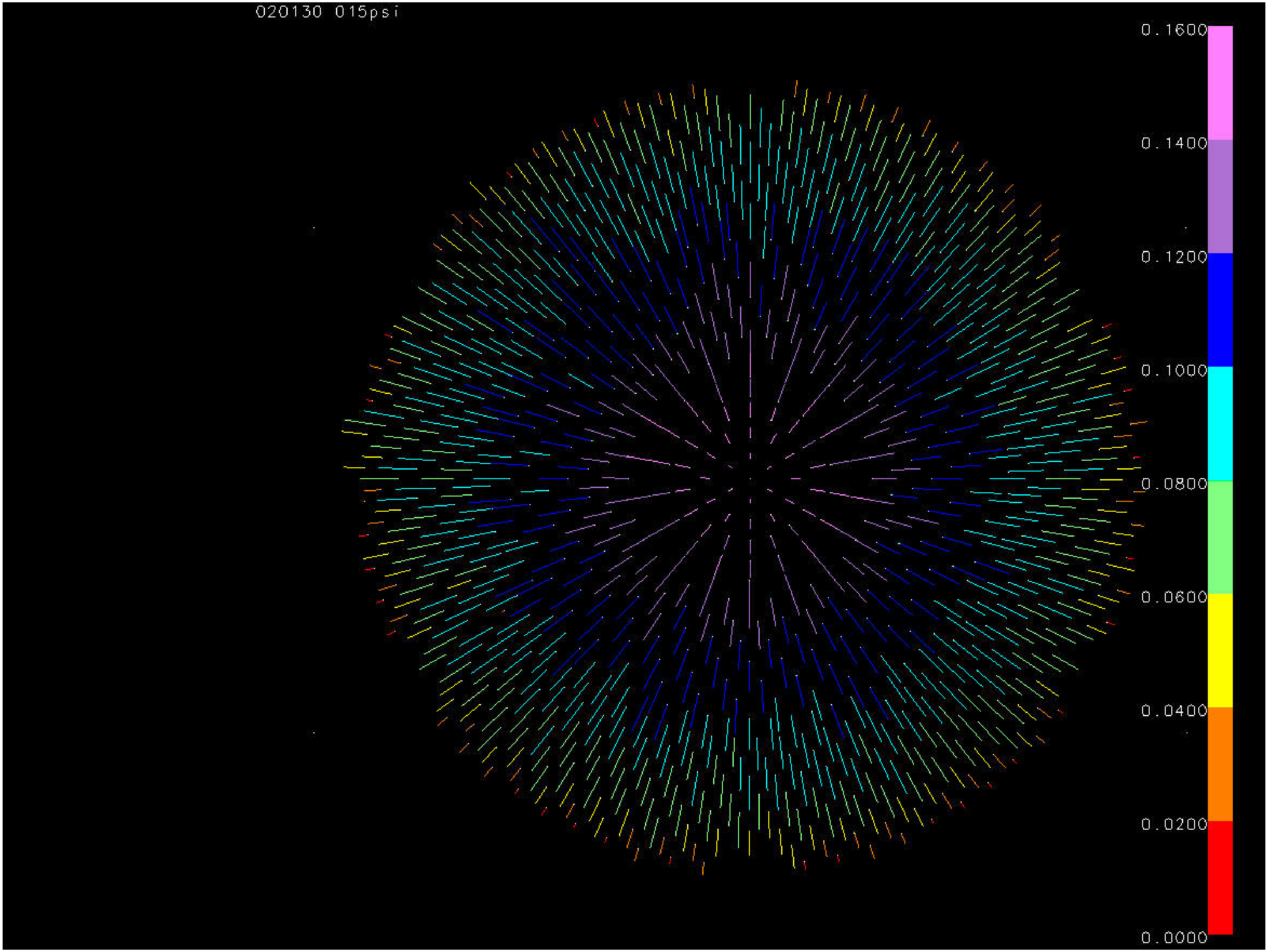
What's left is f(pressure).

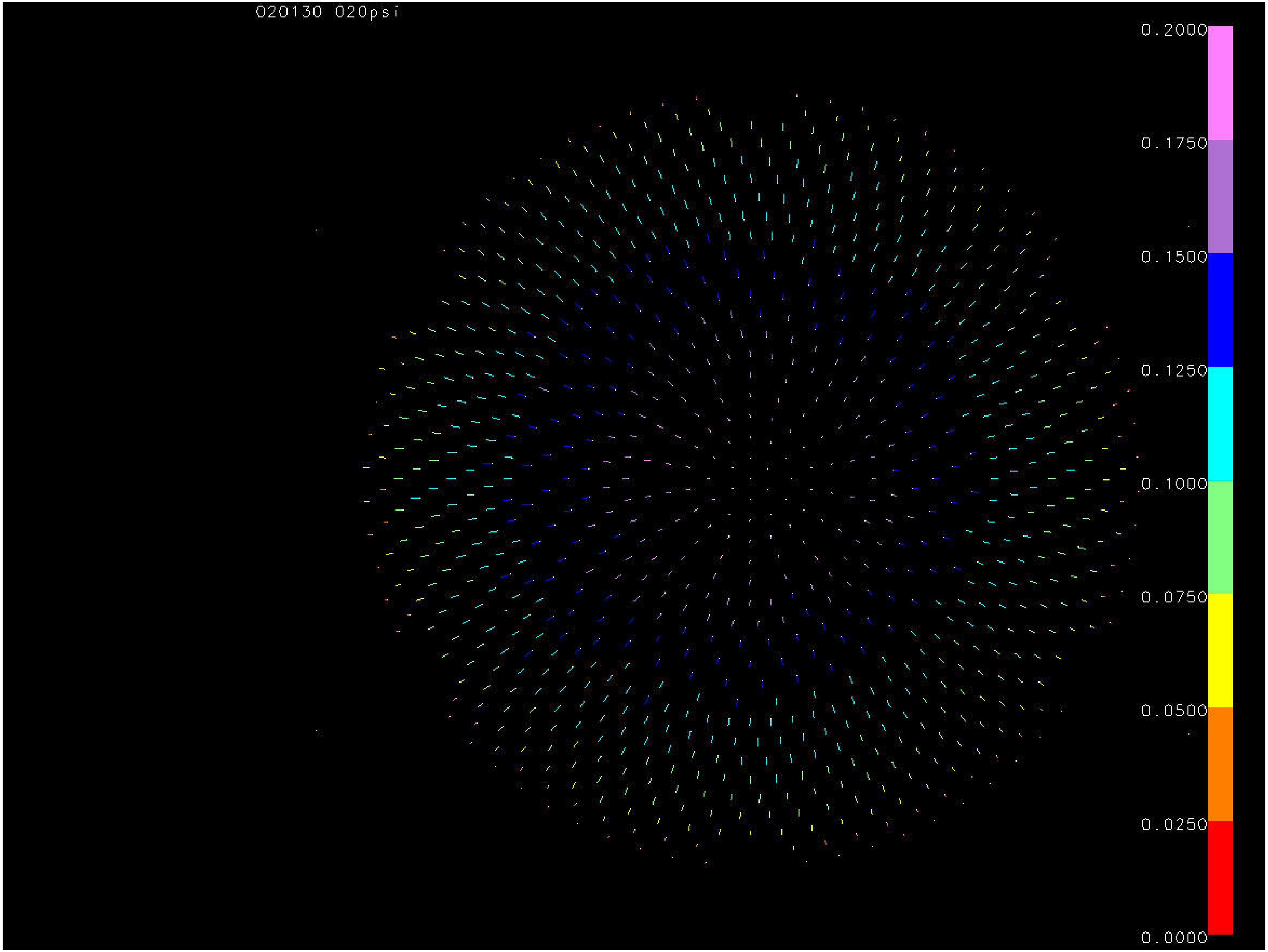


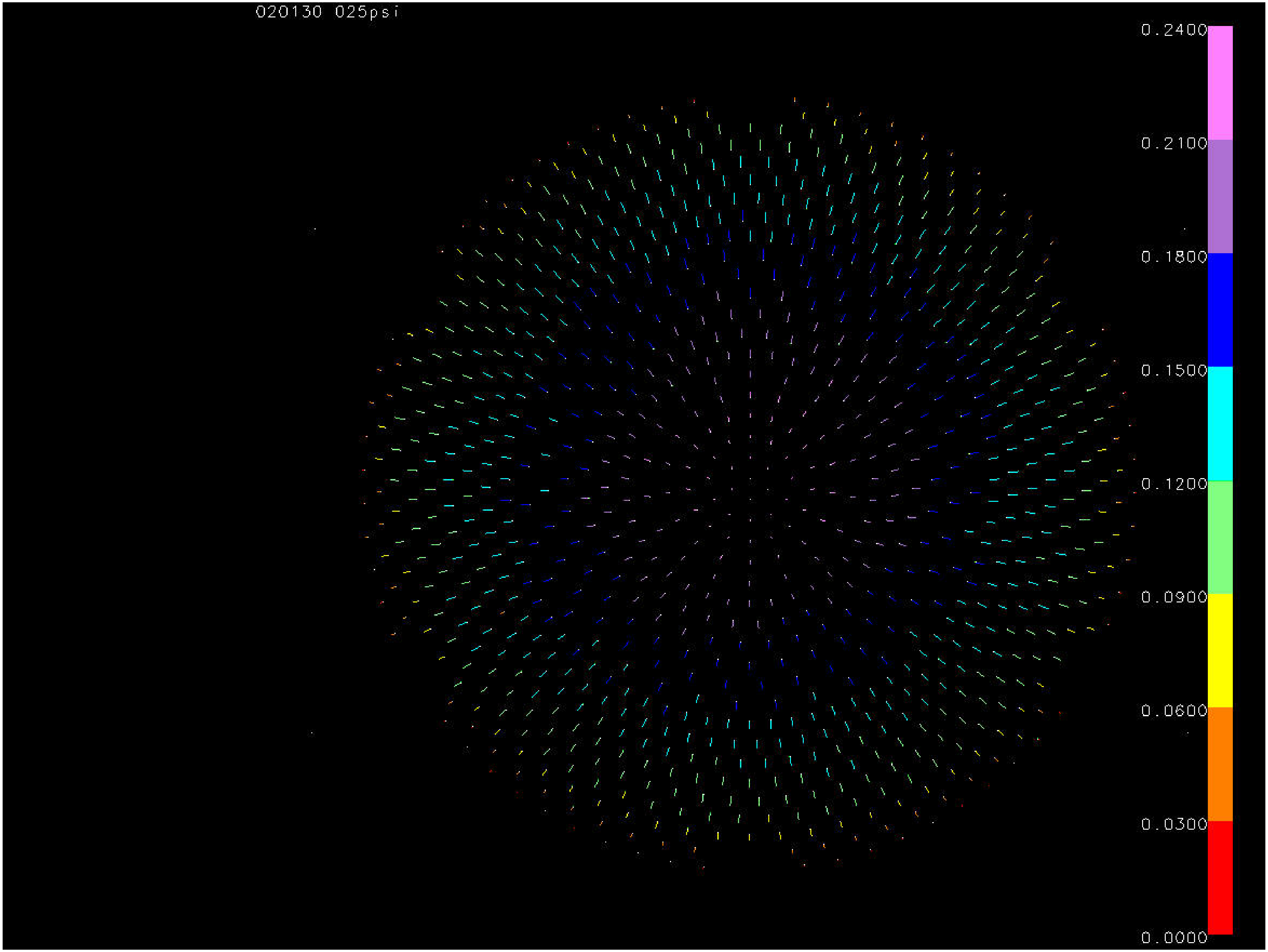
Observe the whisker plots to check for any asymmetry in the deformation of the window as the pressure is increased...

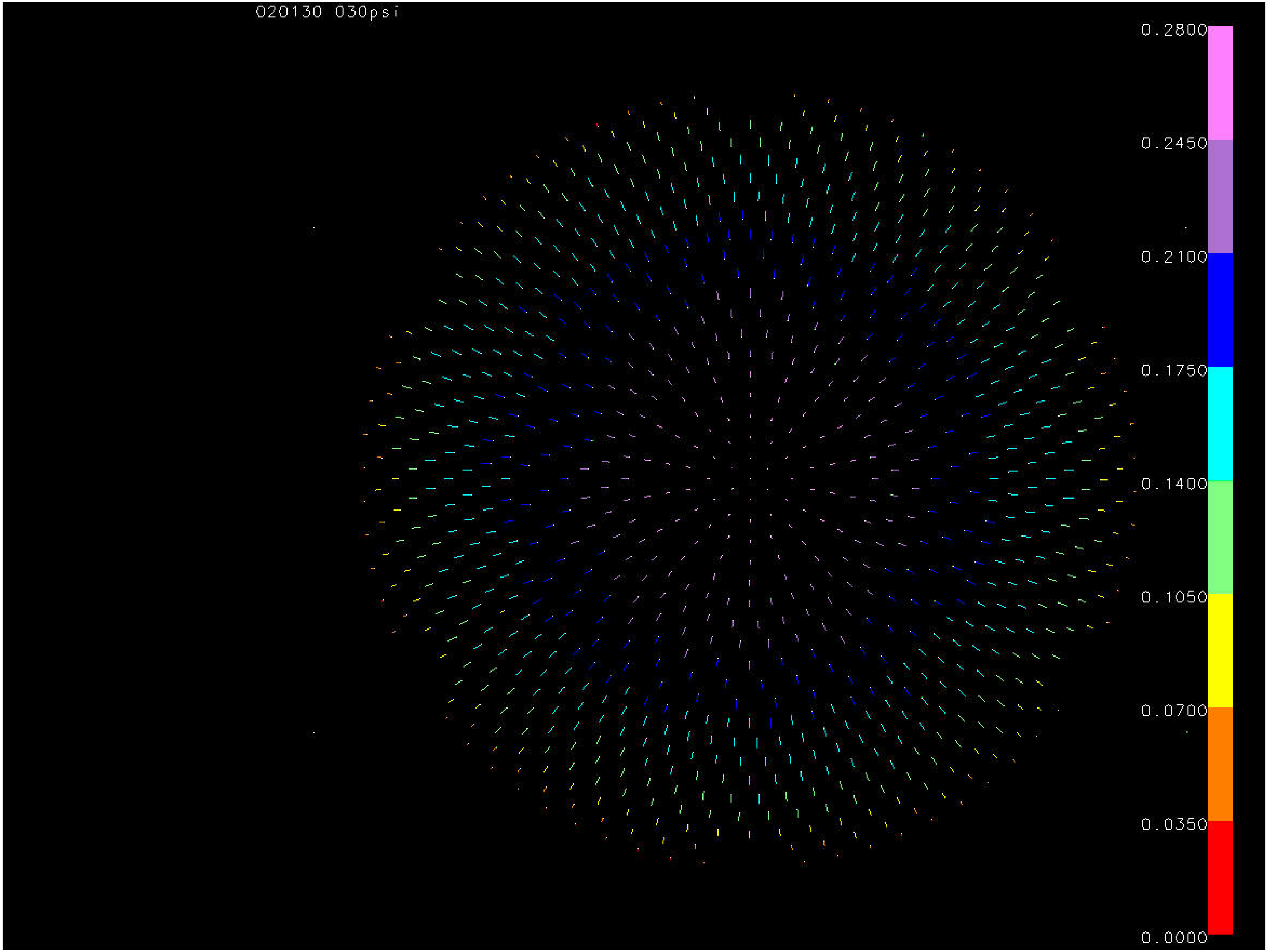

020130 005psi
0.027
0.024
0.020
0.017
0.014
0.010
0.007
0.003
0.000


020130 010psi
0.0800
0.0700
0.0600
0.0500
0.0400
0.0300
0.0200
0.0100
0.0000

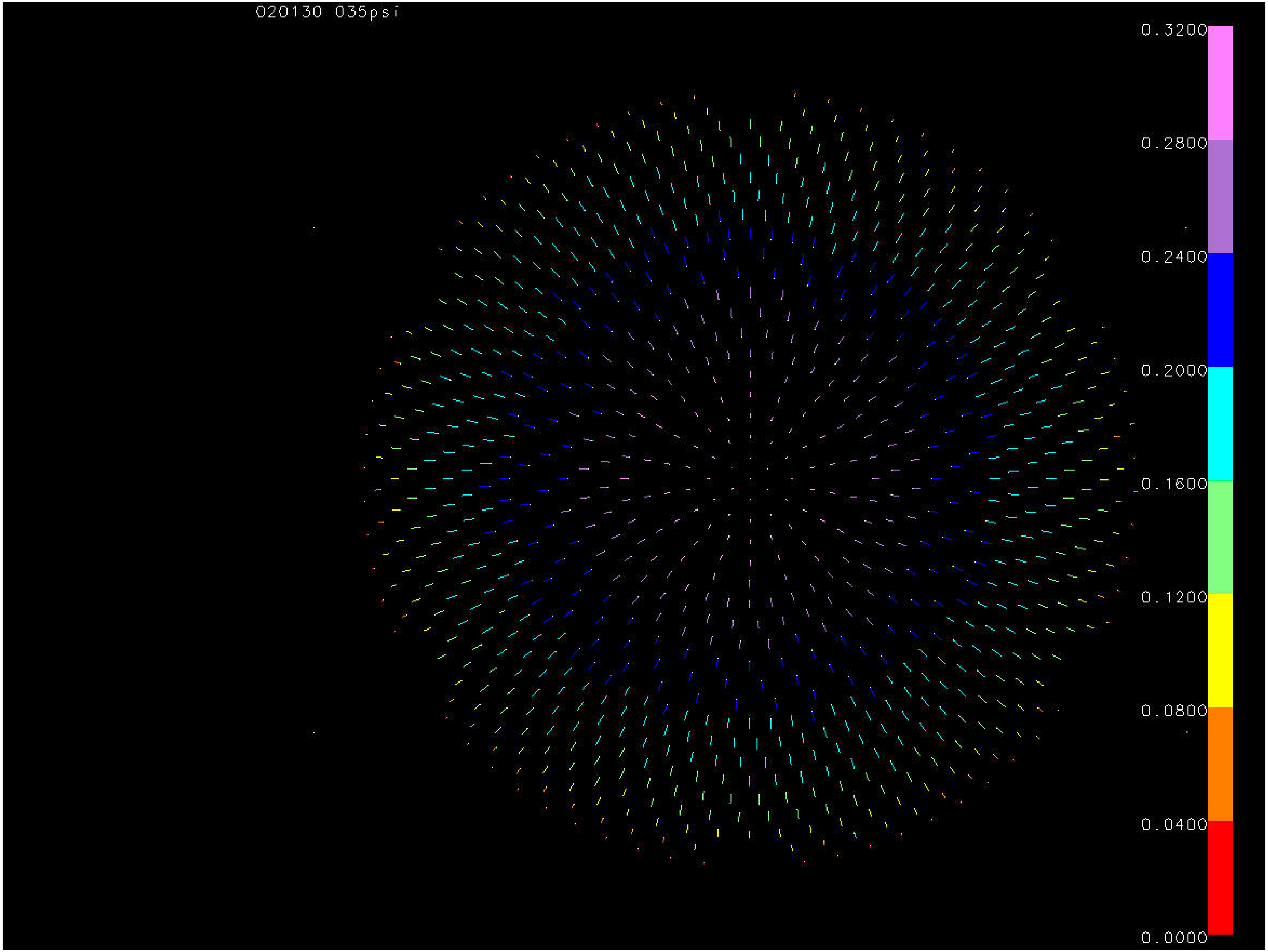

020130 015psi
0.1600
0.1400
0.1200
0.1000
0.0800
0.0600
0.0400
0.0200
0.0000

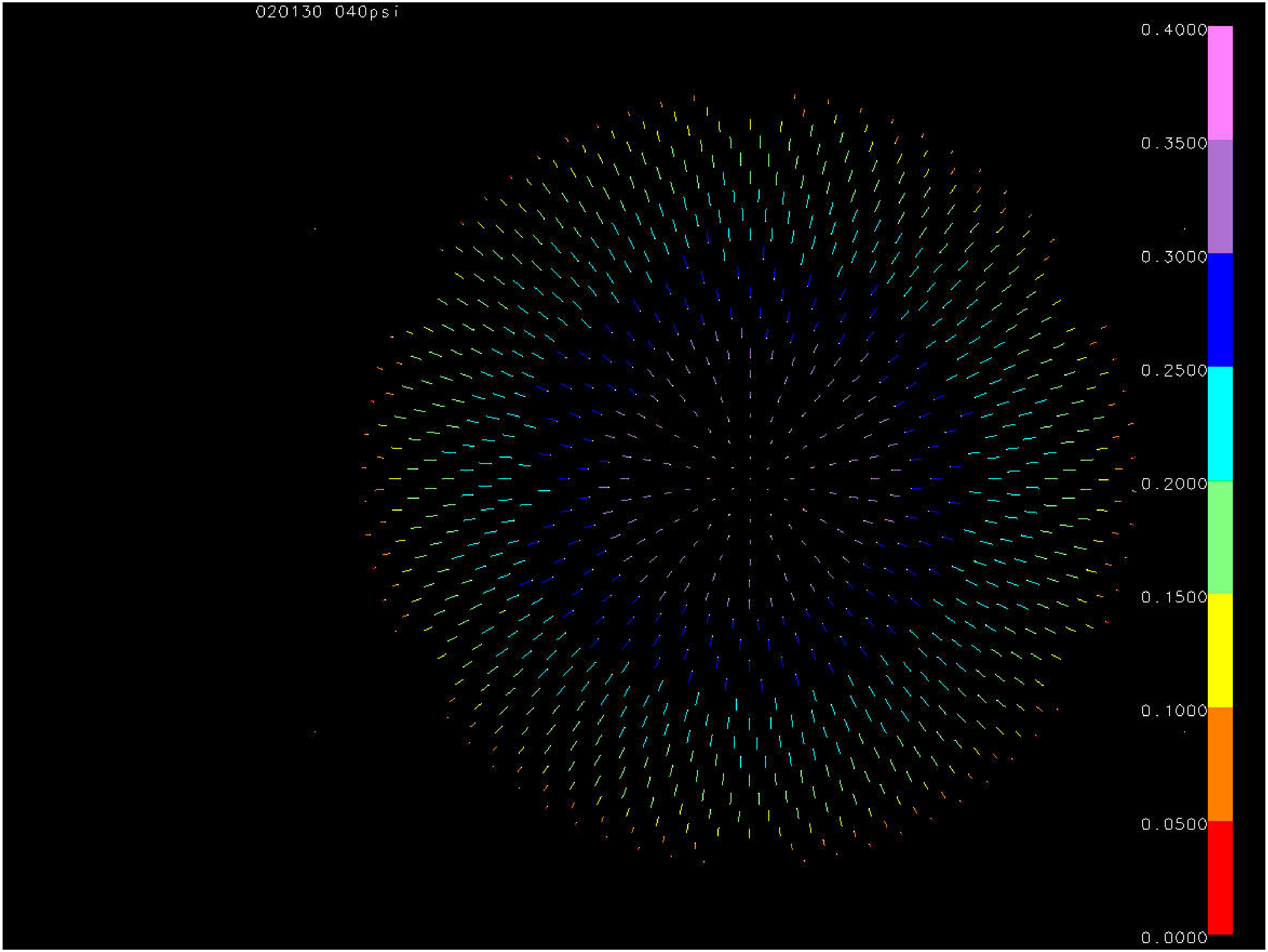

020130 020psi
0.2000
0.1750
0.1500
0.1250
0.1000
0.0750
0.0500
0.0250
0.0000

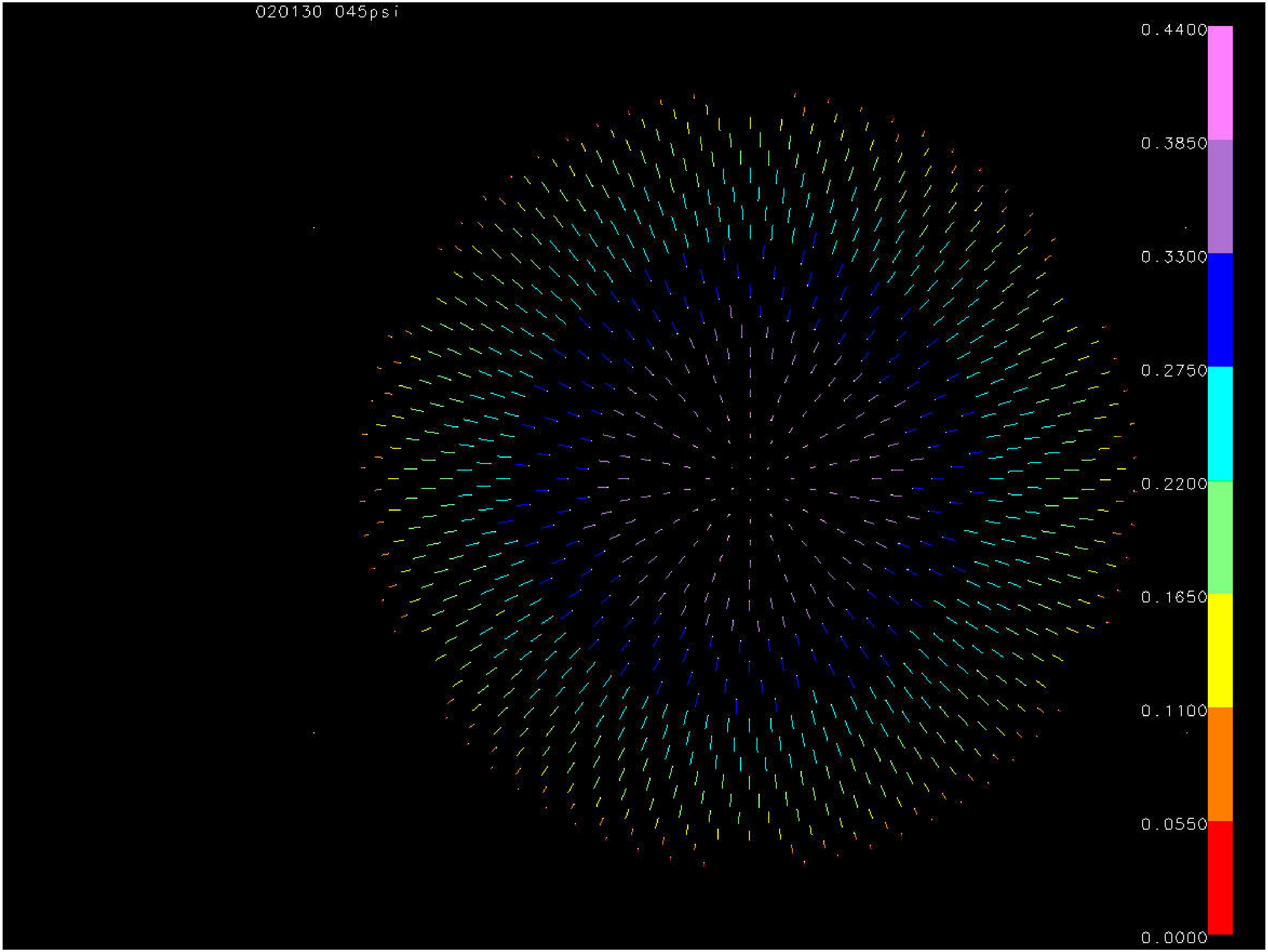

020130 025psi
0.2400
0.2100
0.1800
0.1500
0.1200
0.0900
0.0600
0.0300
0.0000

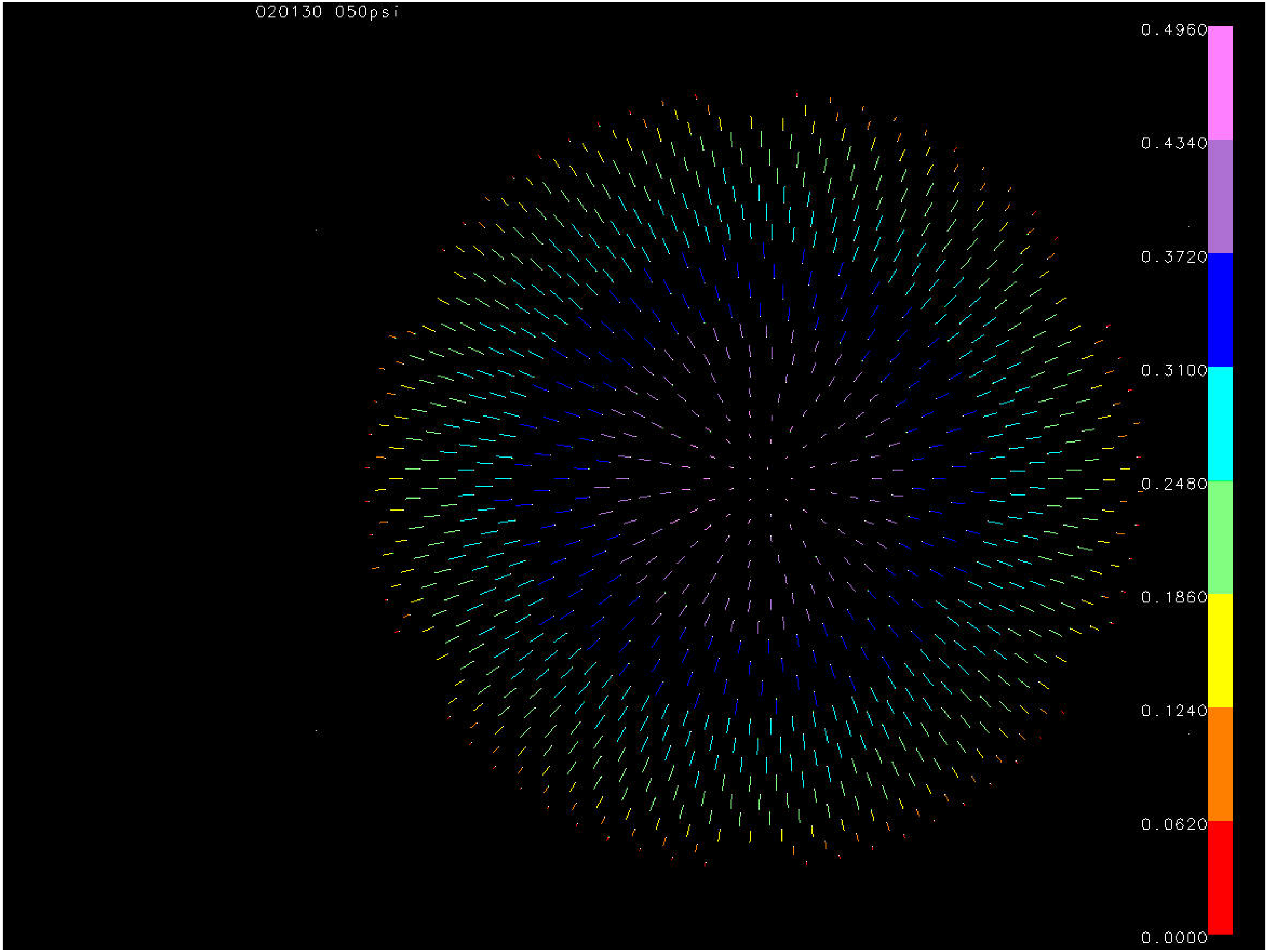


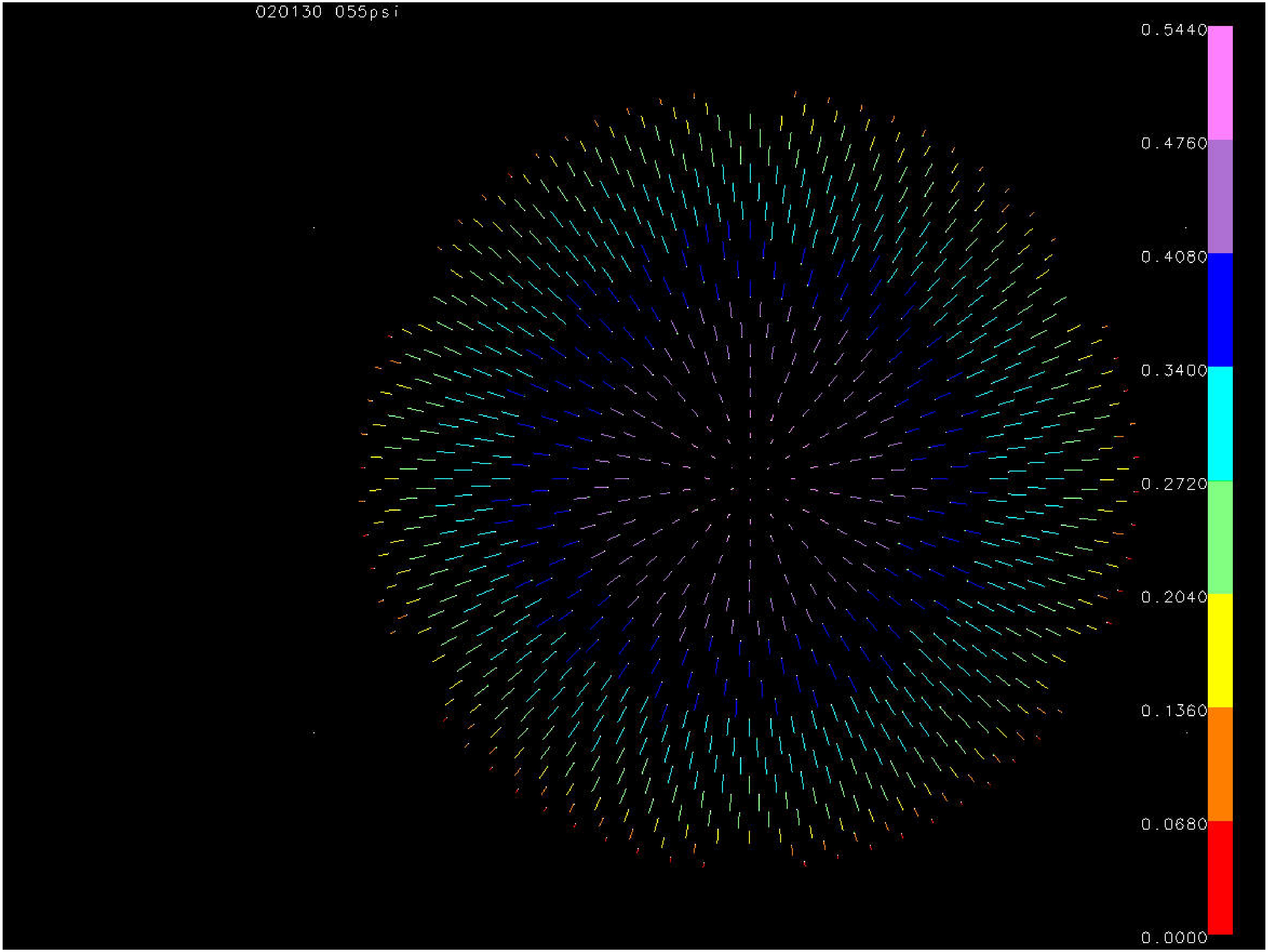
020130 030psi
0.2800
0.2450
0.2100
0.1750
0.1400
0.1050
0.0700
0.0350
0.0000

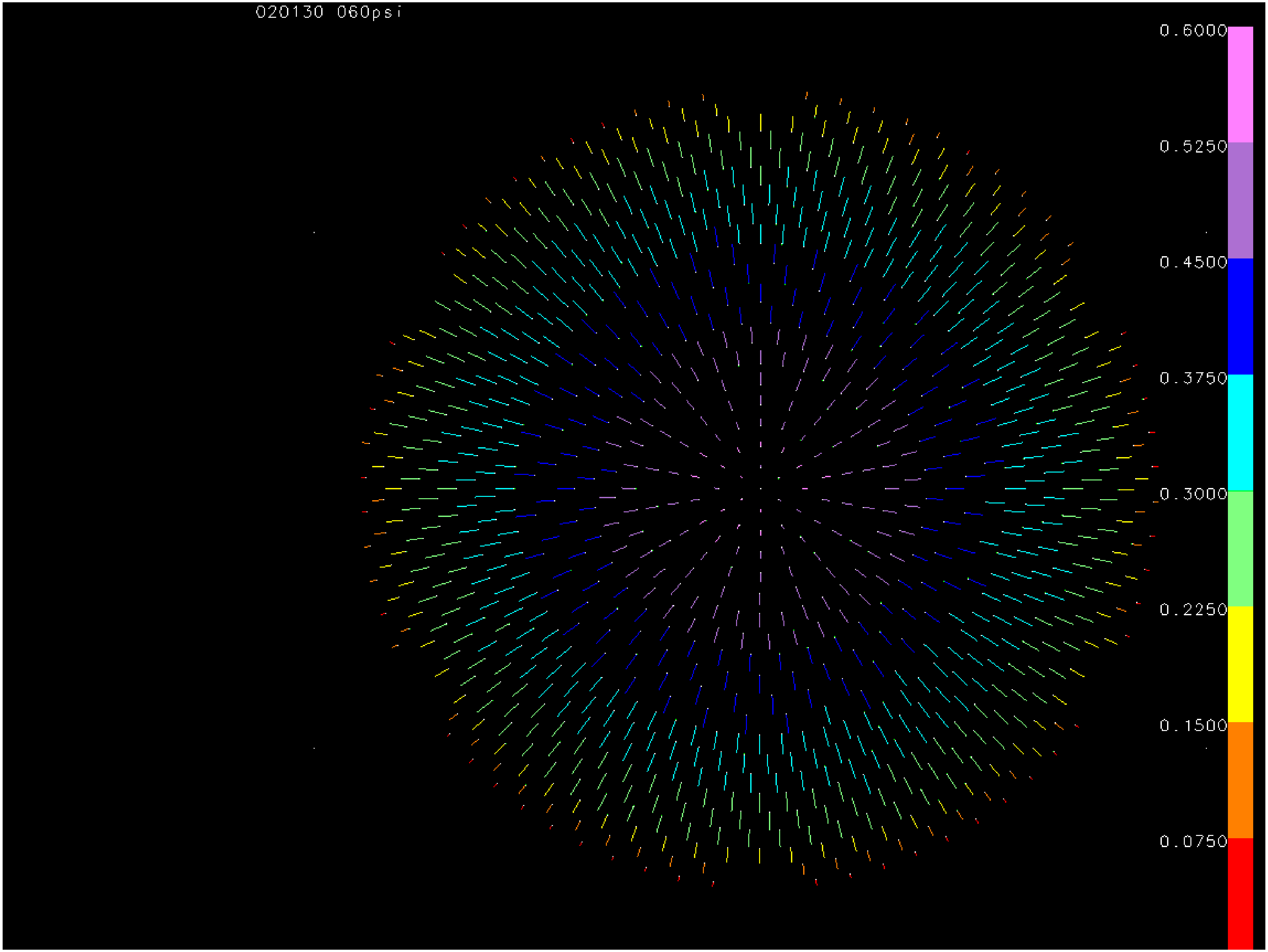

020130 035psi
0.3200
0.2800
0.2400
0.2000
0.1600
0.1200
0.0800
0.0400
0.0000

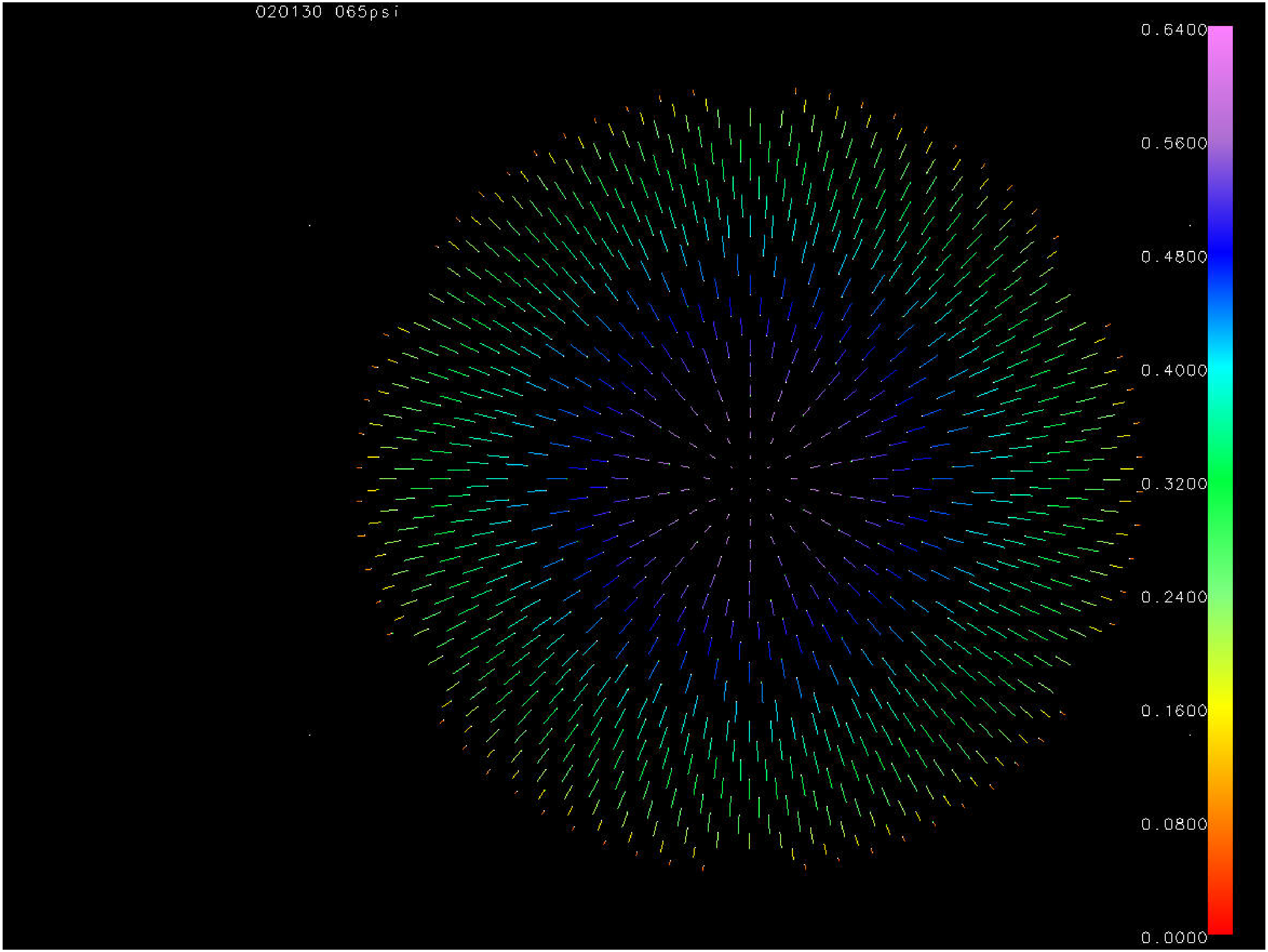

020130 040psi
0.4000
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000


020130 045psi
0.4400
0.3850
0.3300
0.2750
0.2200
0.1650
0.1100
0.0550
0.0000

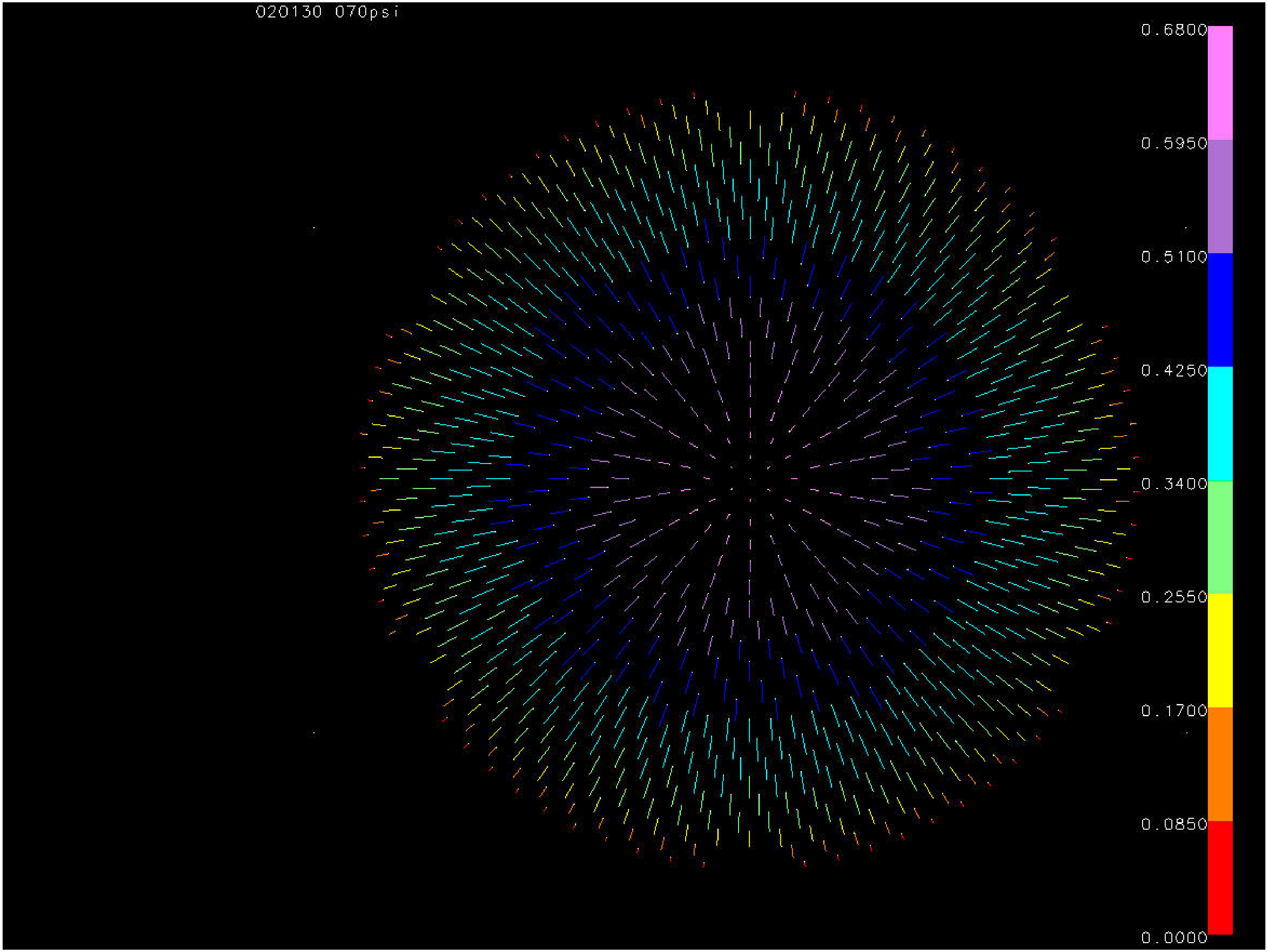

020130 050psi
0.4960
0.4340
0.3720
0.3100
0.2480
0.1860
0.1240
0.0620
0.0000

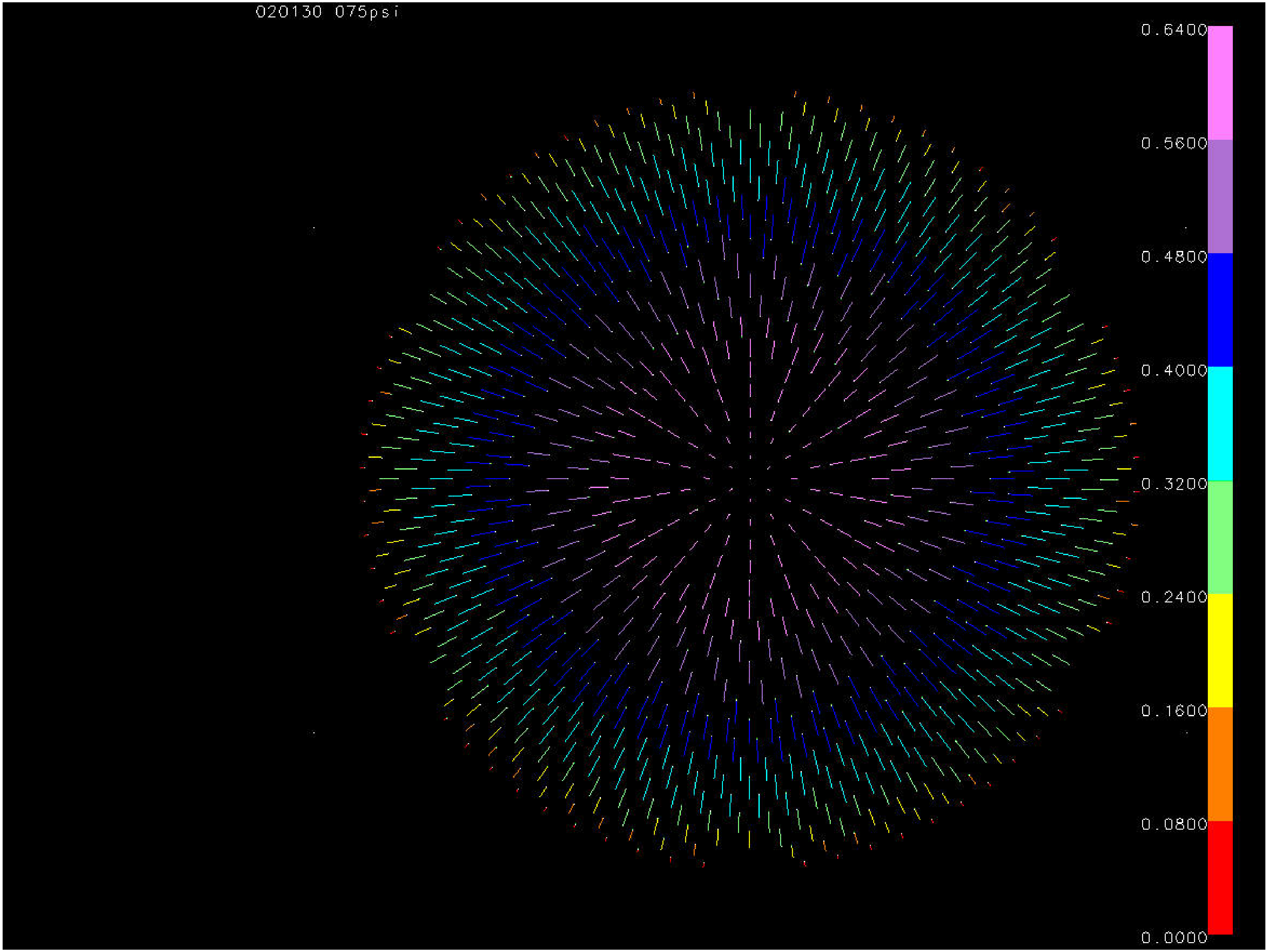

020130 055psi
0.5440
0.4760
0.4080
0.3400
0.2720
0.2040
0.1360
0.0680
0.0000

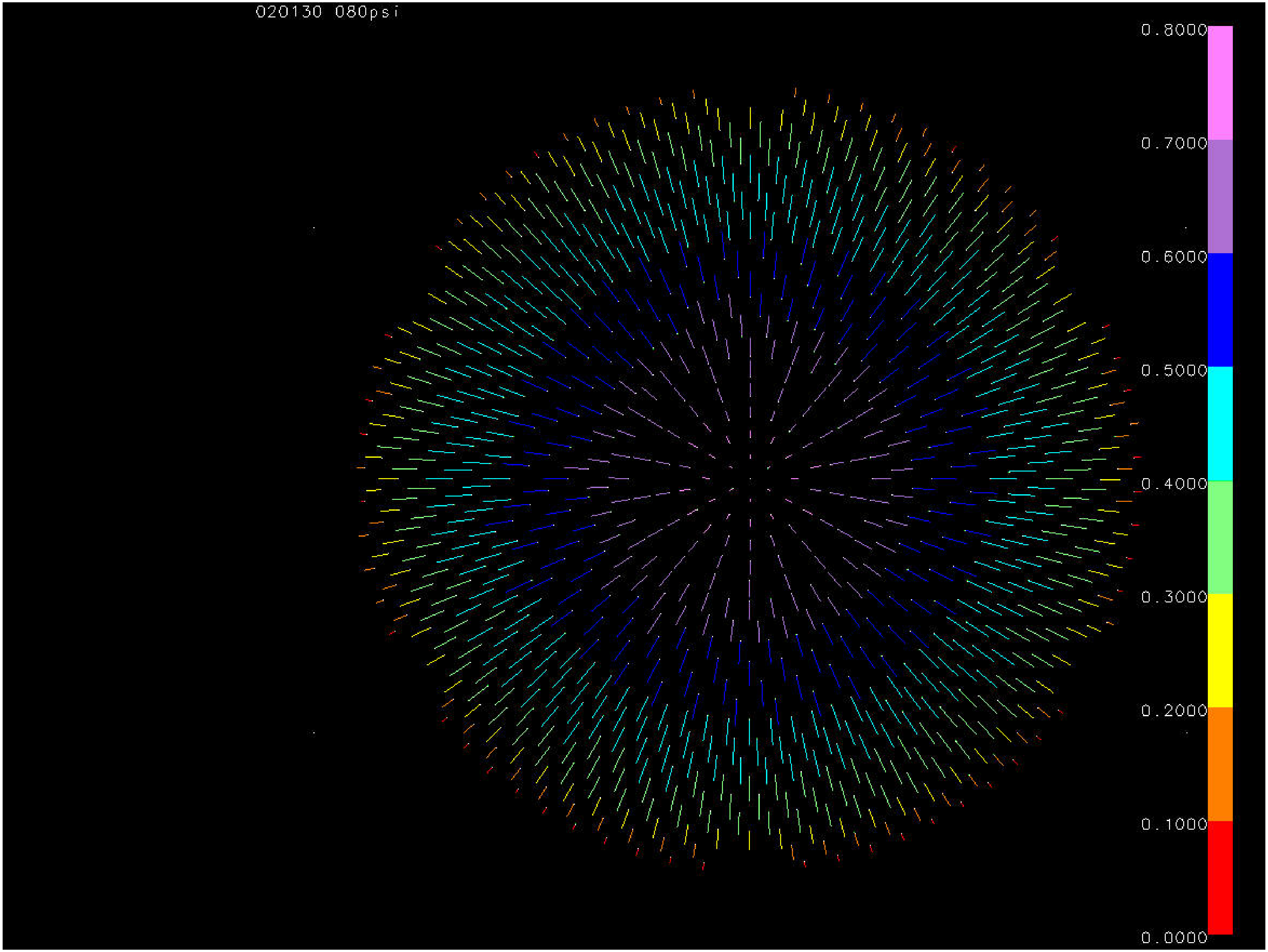

020130 060psi
0.6000
0.5250
0.4500
0.3750
0.3000
0.2250
0.1500
0.0750

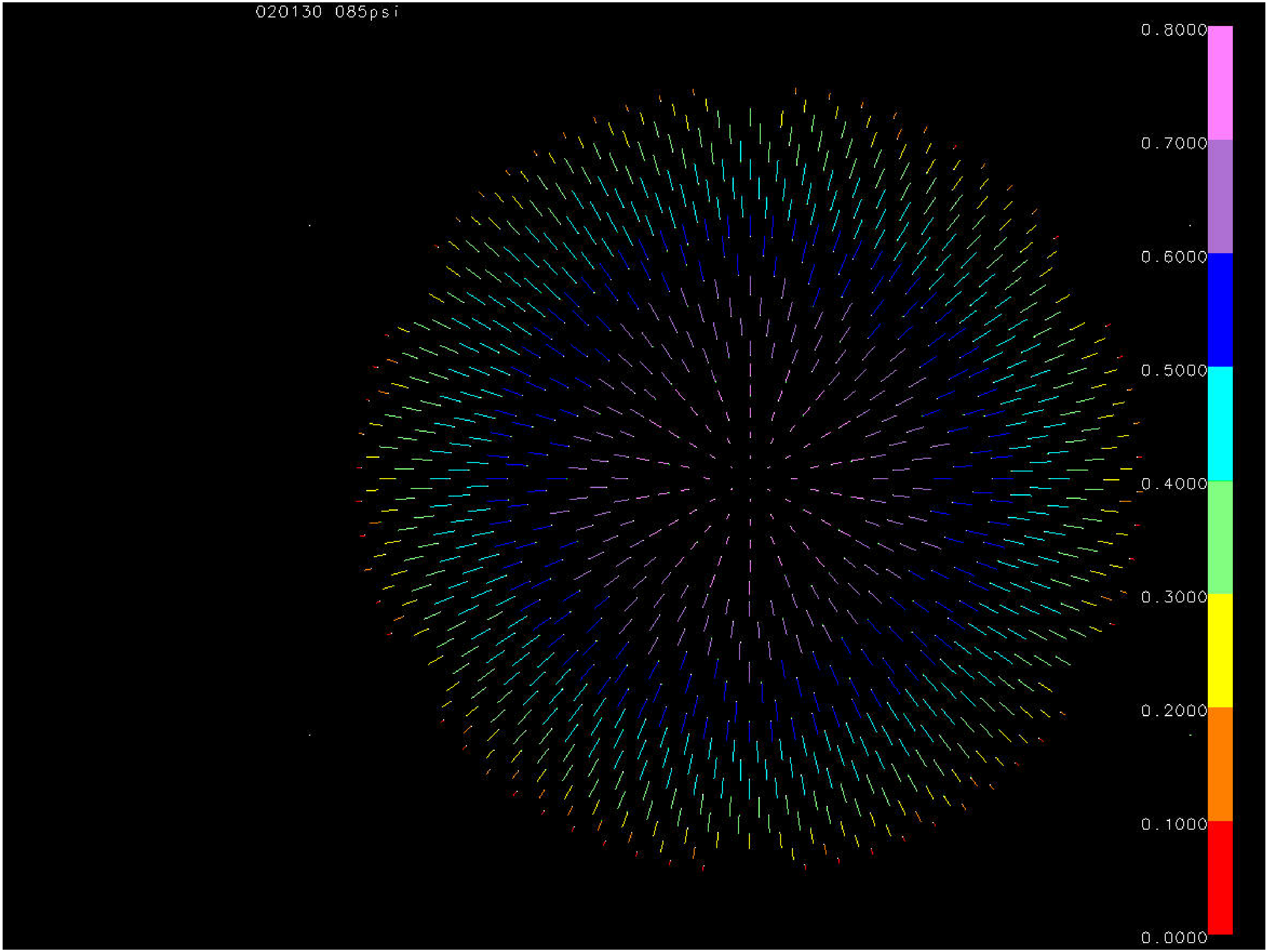


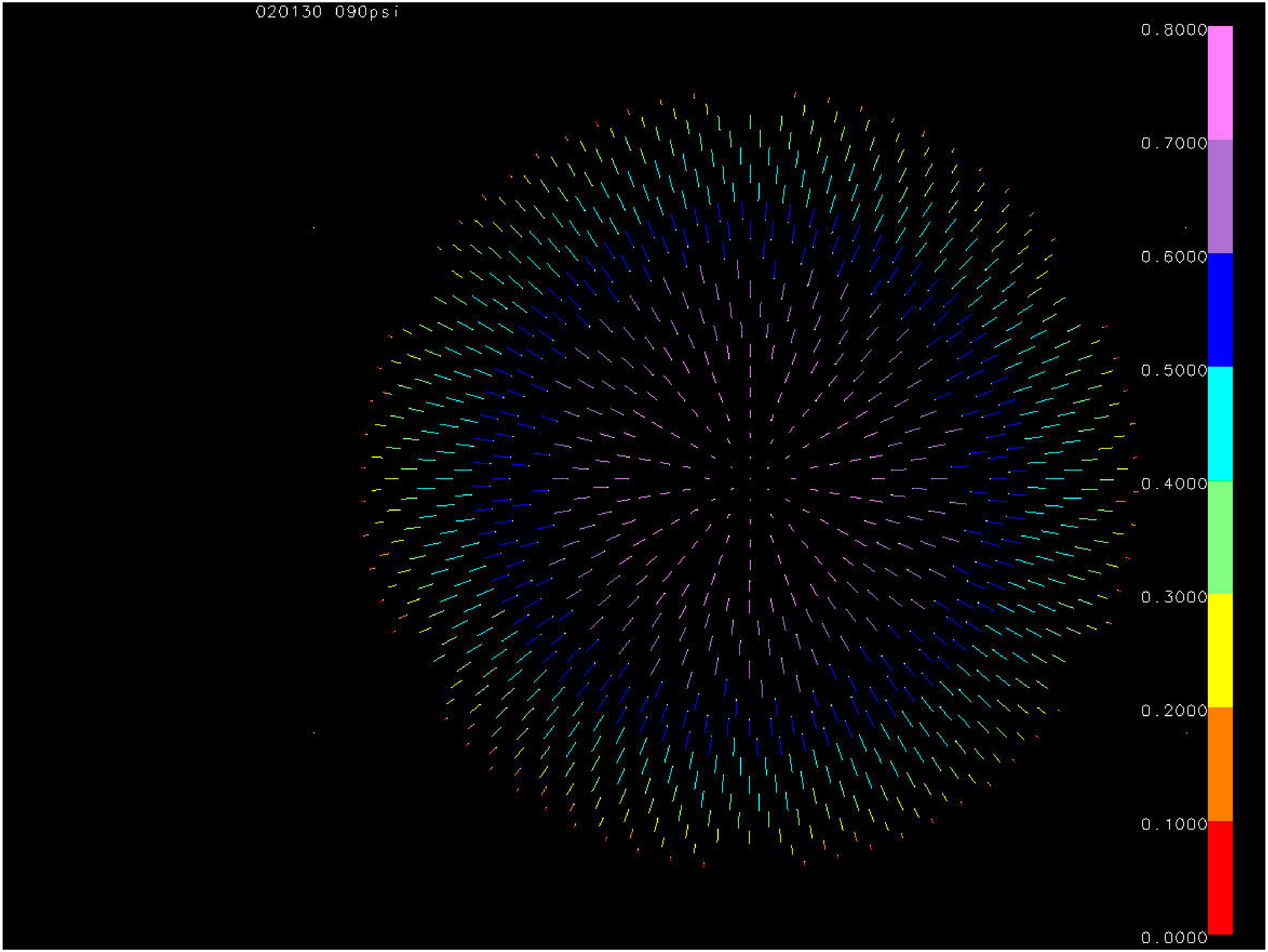
020130 065psi
0.6400
0.5600
0.4800
0.4000
0.3200
0.2400
0.1600
0.0800
0.0000

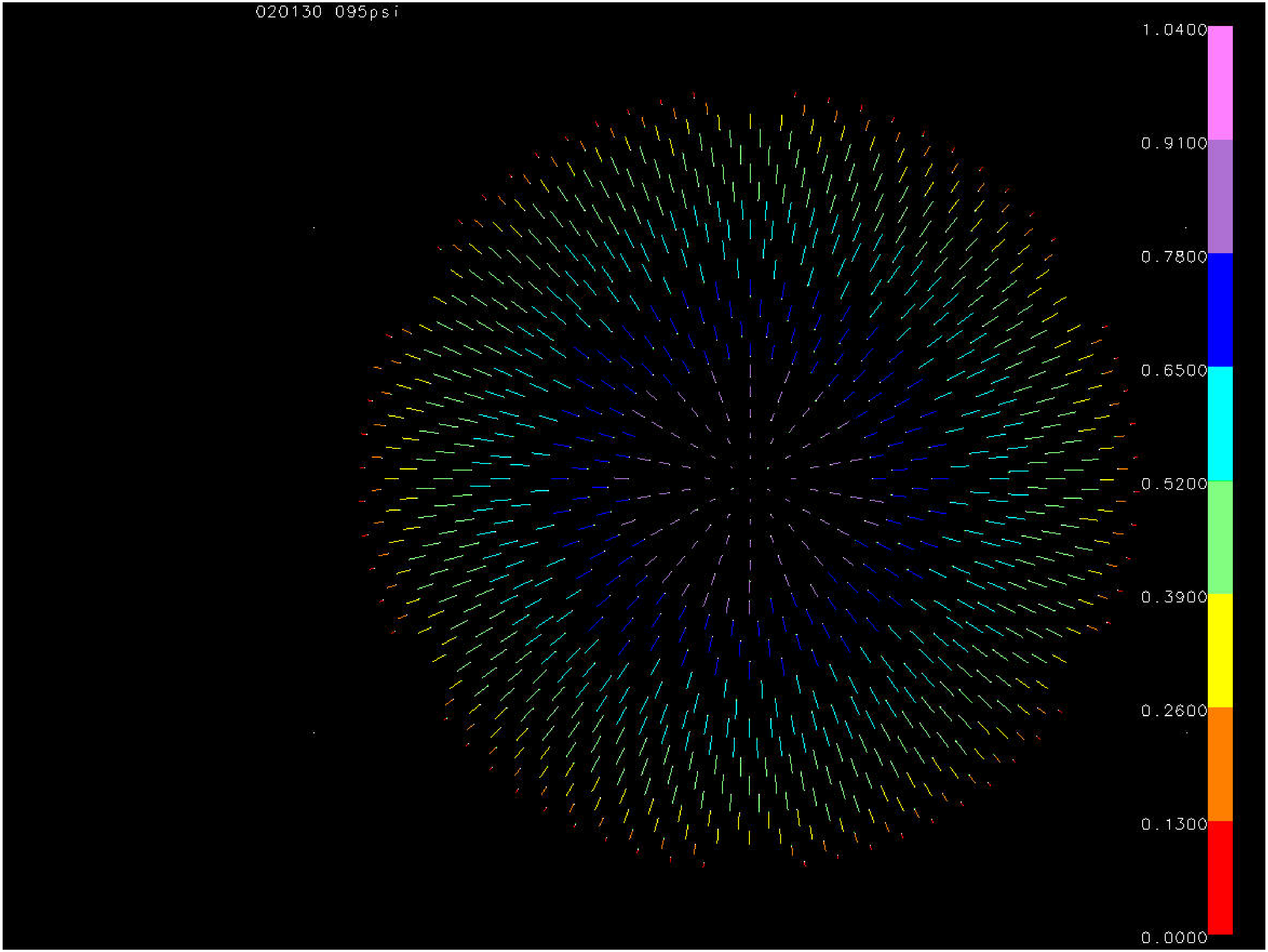

020130 070psi
0.6800
0.5950
0.5100
0.4250
0.3400
0.2550
0.1700
0.0850
0.0000

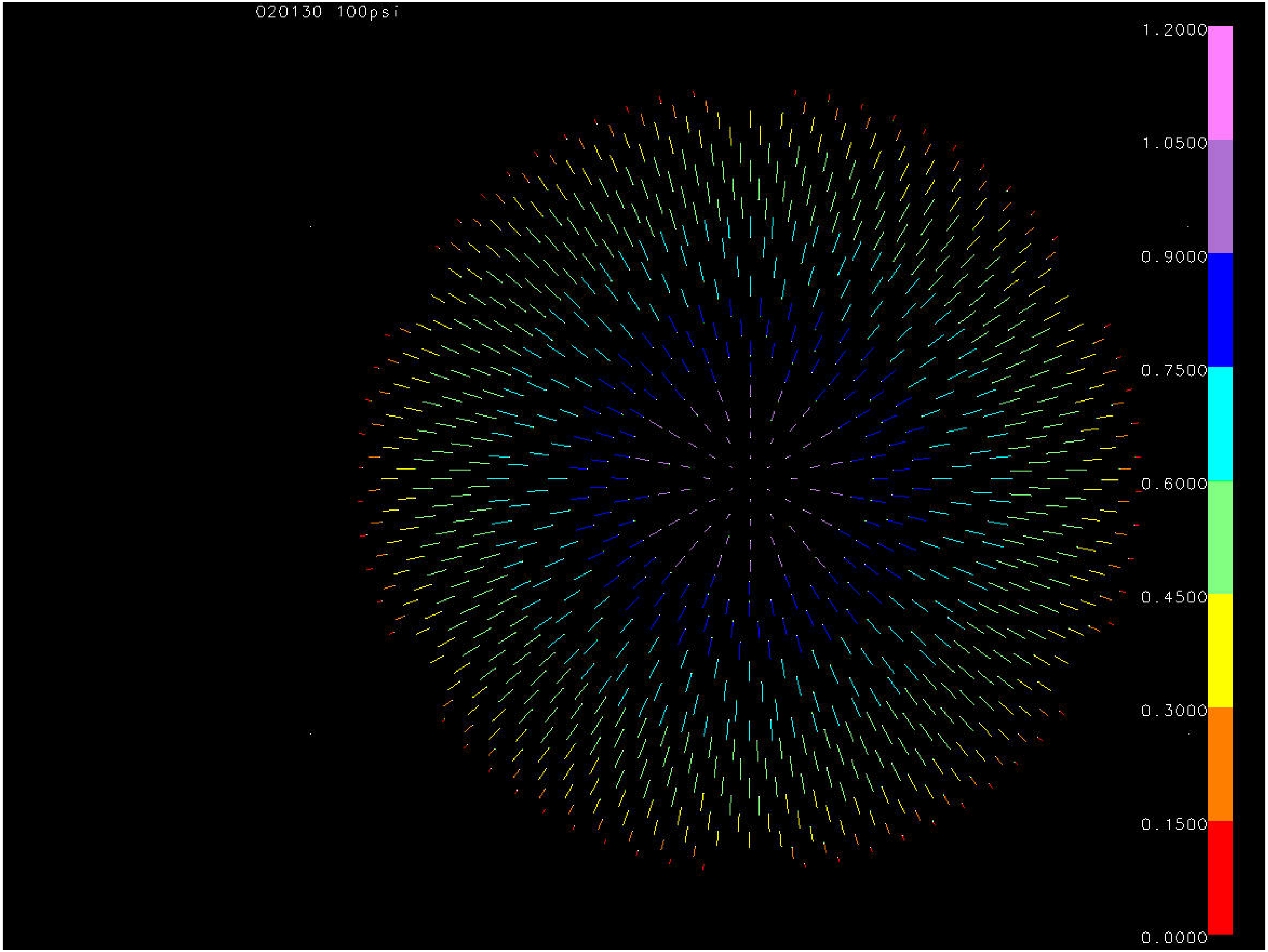

020130 075psi
0.6400
0.5600
0.4800
0.4000
0.3200
0.2400
0.1600
0.0800
0.0000

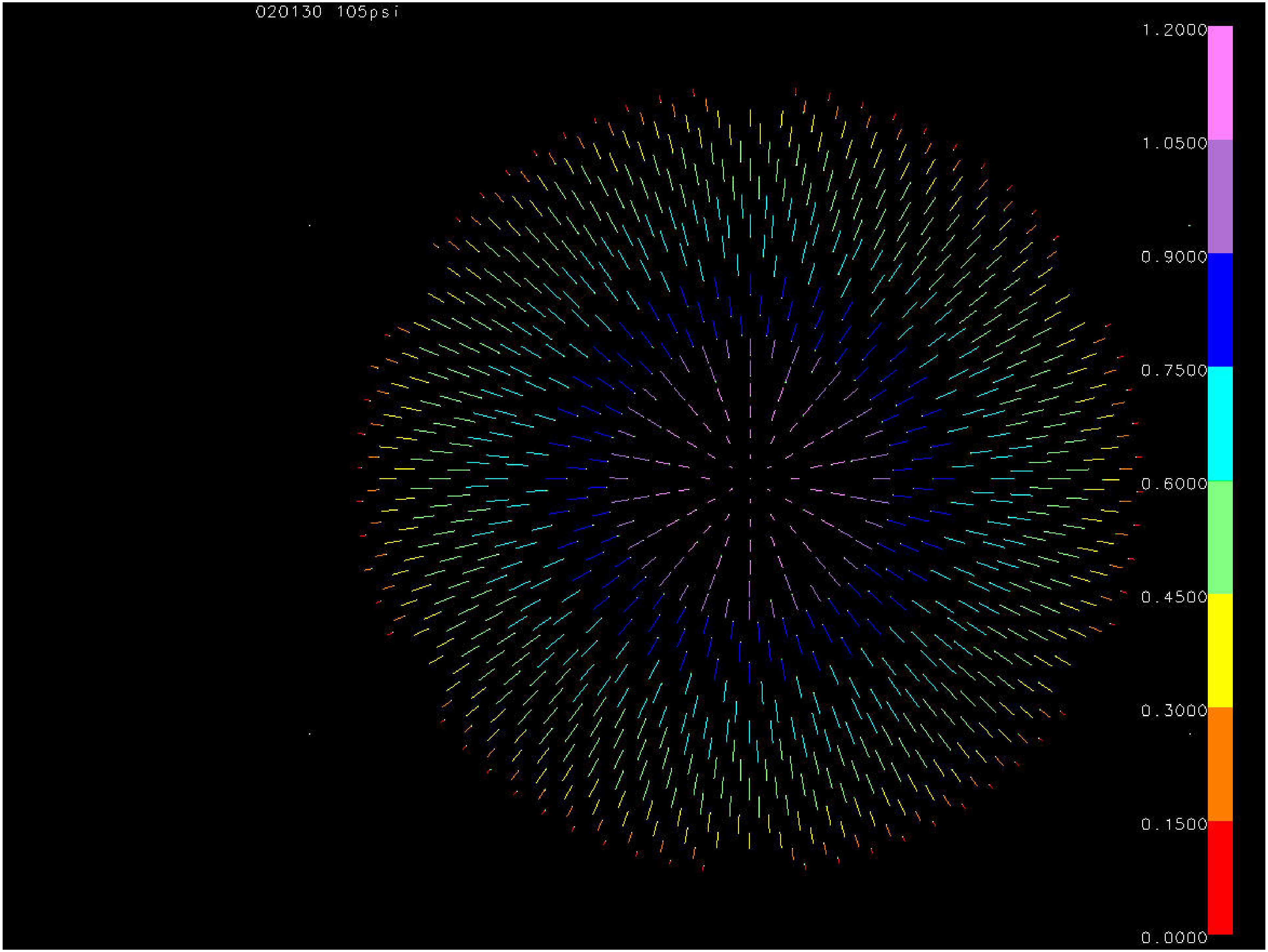

020130 080psi
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000

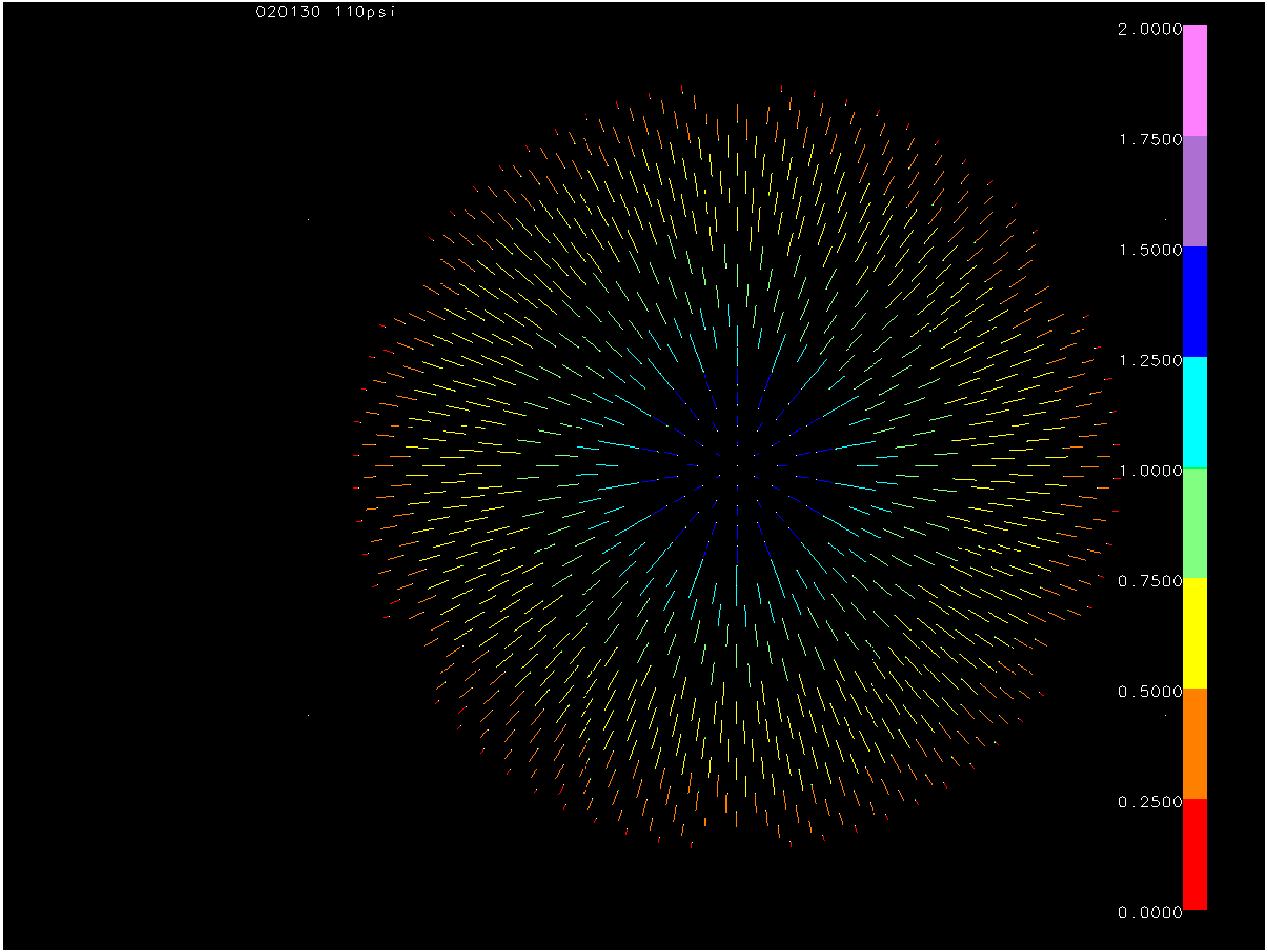

020130 085psi
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000

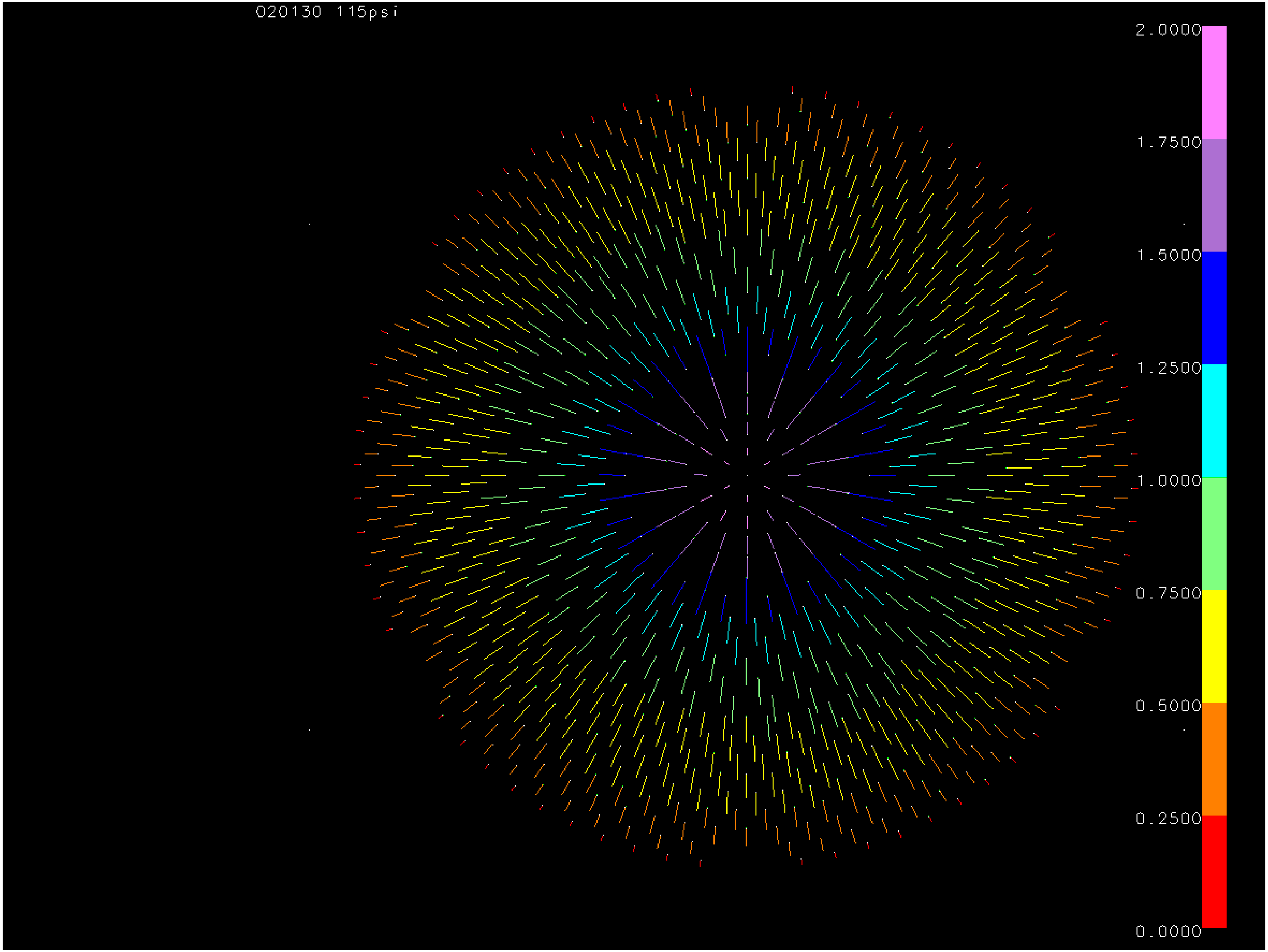

020130 090psi
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000


020130 095psi
1.0400
0.9100
0.7800
0.6500
0.5200
0.3900
0.2600
0.1300
0.0000


020130 100psi
1.2000
1.0500
0.9000
0.7500
0.6000
0.4500
0.3000
0.1500
0.0000


020130 105psi
1.2000
1.0500
0.9000
0.7500
0.6000
0.4500
0.3000
0.1500
0.0000


020130 110psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000



020130 115psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000


020130 120psi
2.0000
1.7500
1.5000
1.2500
1.0000
0.7500
0.5000
0.2500

Mucool history of photogrammetry

- Compare the window's *performance* to FEA
- Observe *characteristics* of the window's performance
- Compare the window's *shape and thickness* to design specifications

Advantages of photogrammetry over CMM

Non-contact

Greater surface coverage

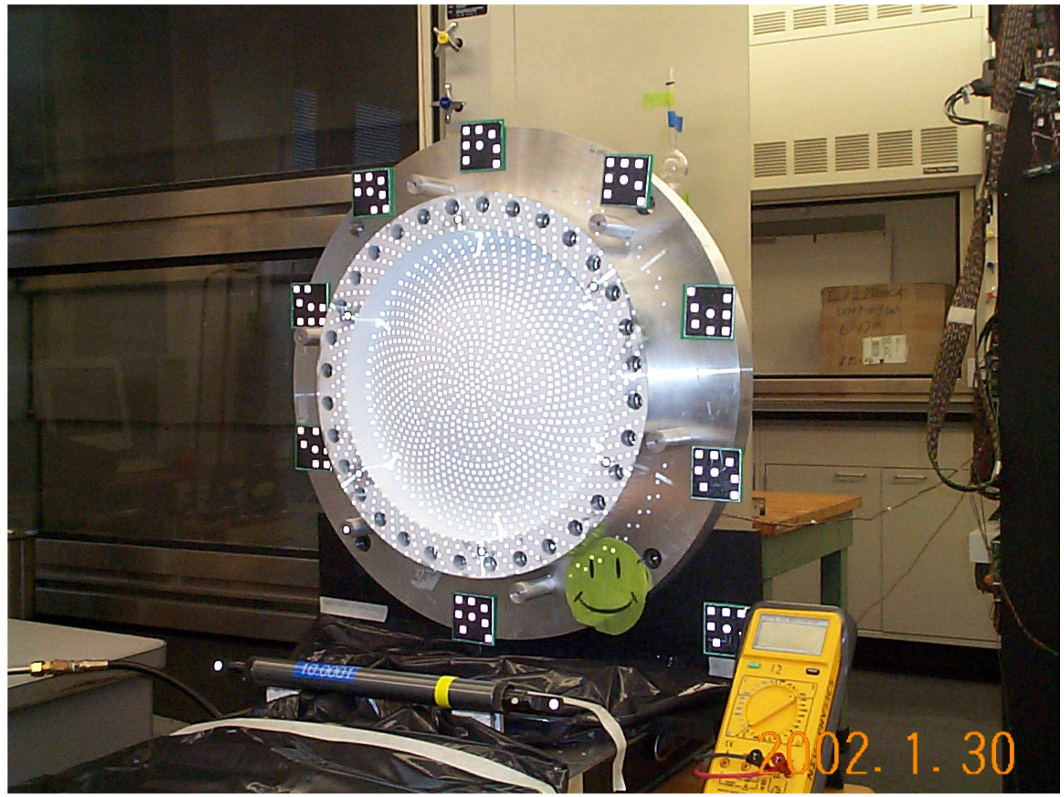
Non-contact

CMM

Photogrammetry

Greater coverage

CMM ~30 points



Photogrammetry ~1000 points

Setup to measure window shape

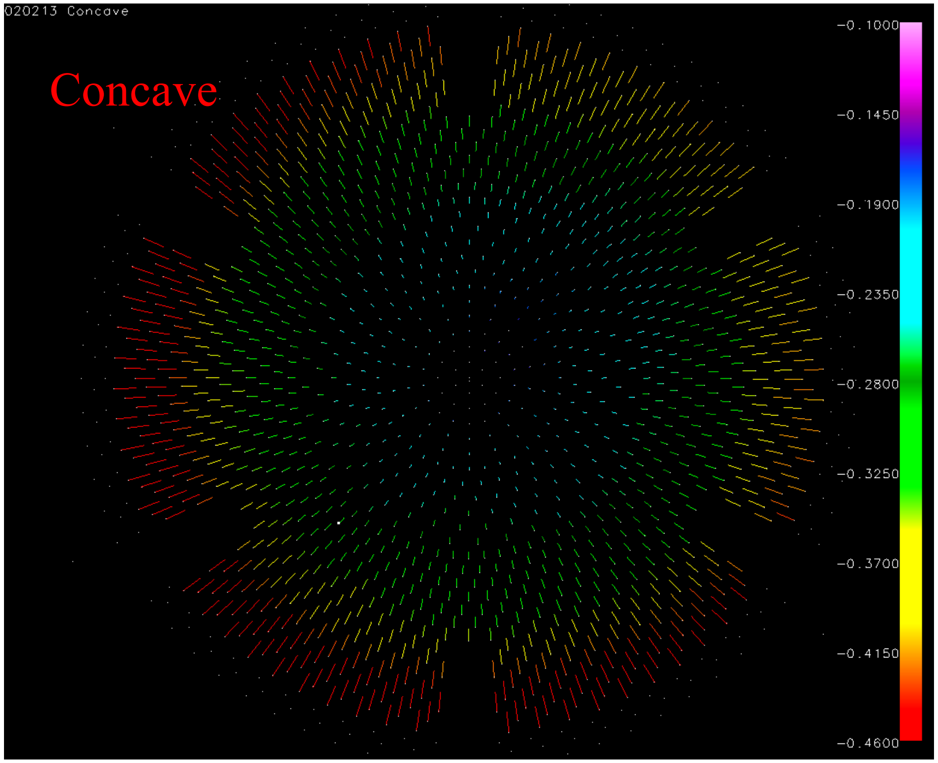
Measure the concave and convex sides of the window by moving the camera and projector from one side of the window to the other.

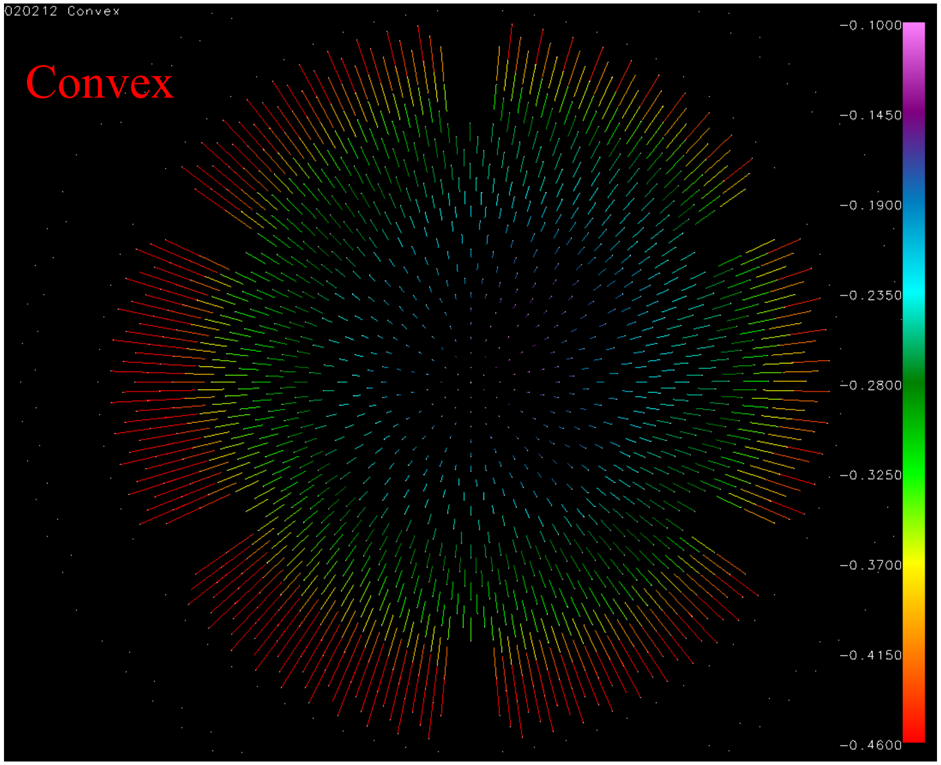
Need for a surface model

Do *not* need to model the surface to compare the window shape with design.

Calculate design z for the x,y of each target & compare to measured z.

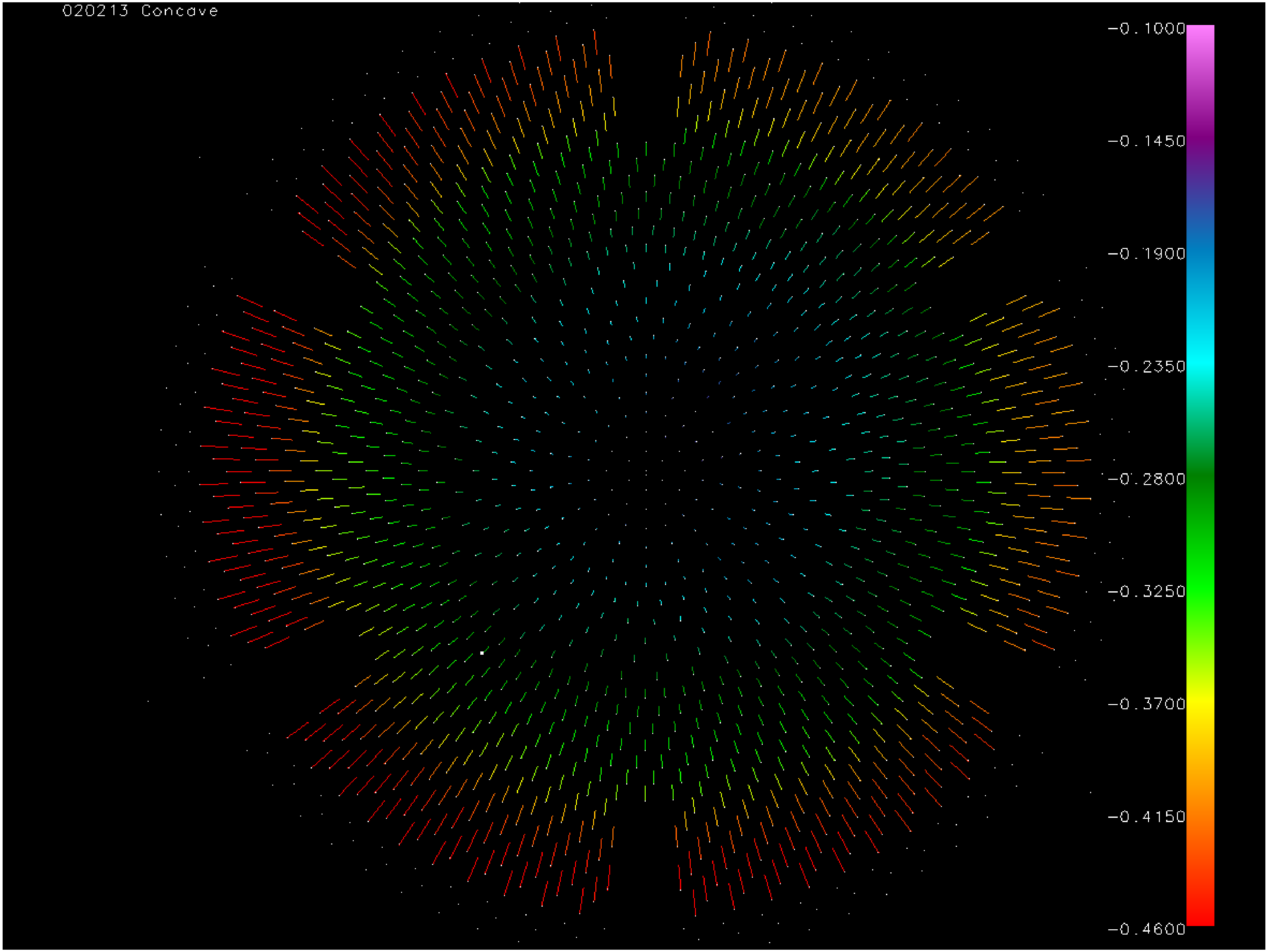
Difference between measured shape and design

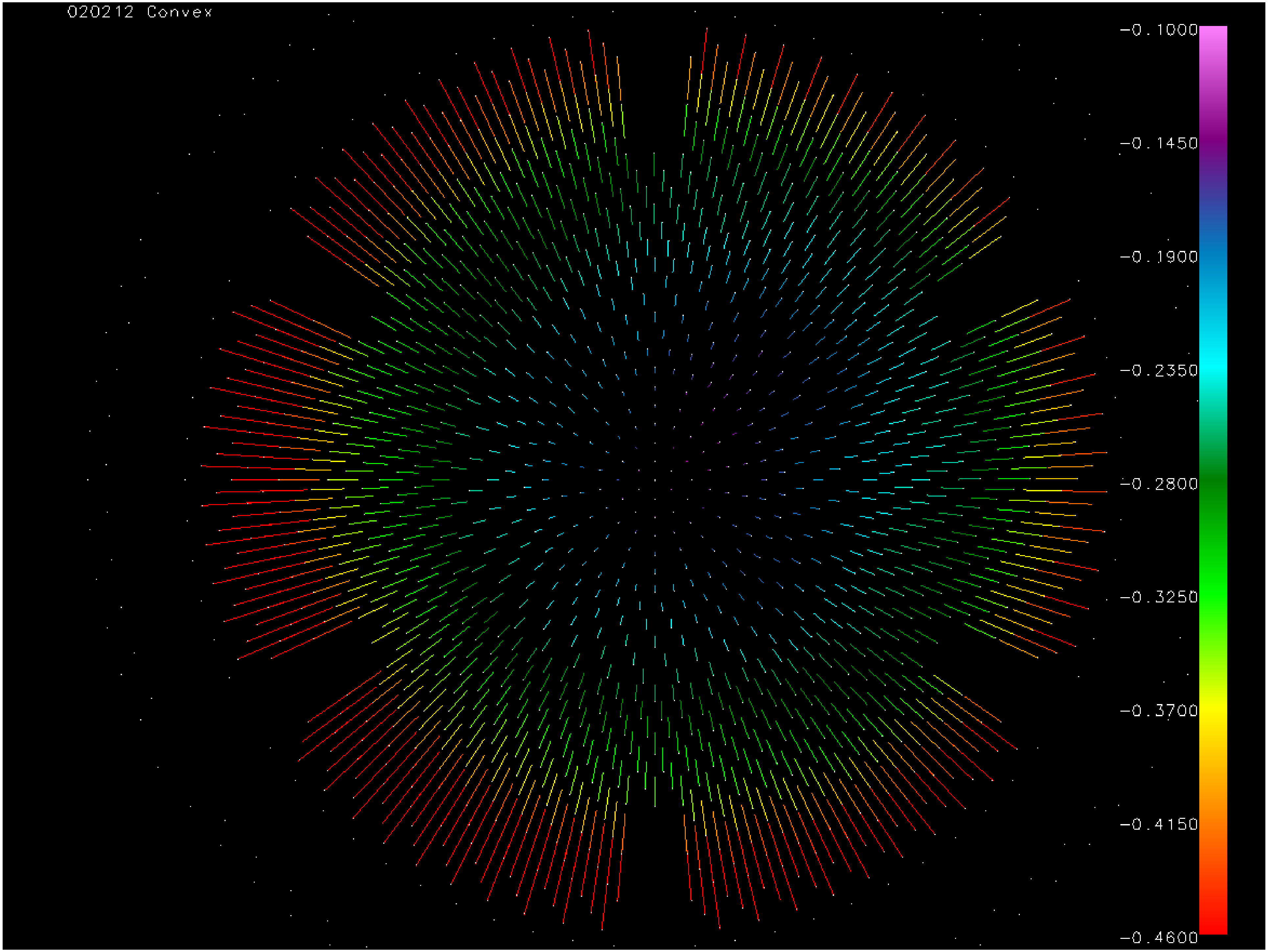




Whisker = z(measured)-z(design)*

*Given the design radius of curvature of the concave and convex surfaces, z(design) was calculated for the (x,y) position of each target


020213 Concave
-0.1000
-0.1450
-0.1900
-0.2350
-0.2800
-0.3250
-0.3700
-0.4150
-0.4600



020212 Convex
-0.1000
-0.1450
-0.1900
-0.2350
-0.2800
-0.3250
-0.3700
-0.4150
-0.4600

The FEA sensitivity analyses emphasize
the need to accurately determine the thickness of the window.

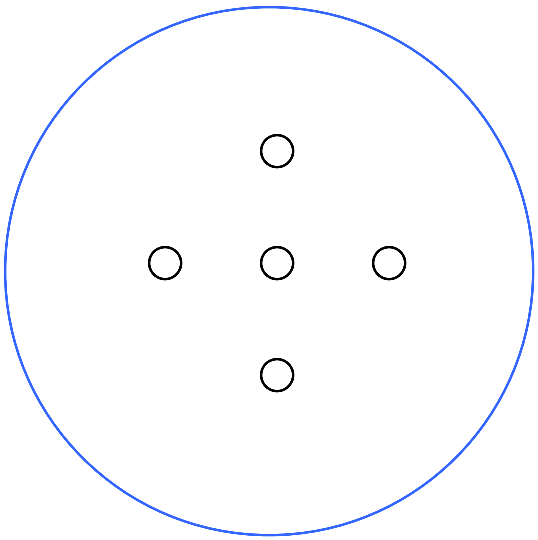
Need for a surface model

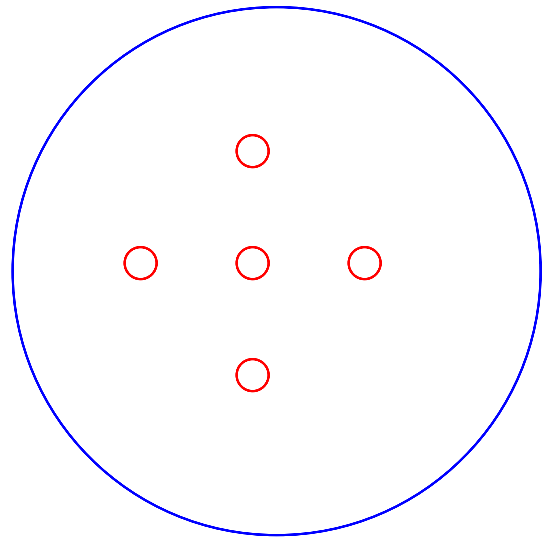
A surface model *is* needed to determine the thickness

It is necessary to determine z for *matching pairs* of x,y on the concave and convex surfaces or the window.

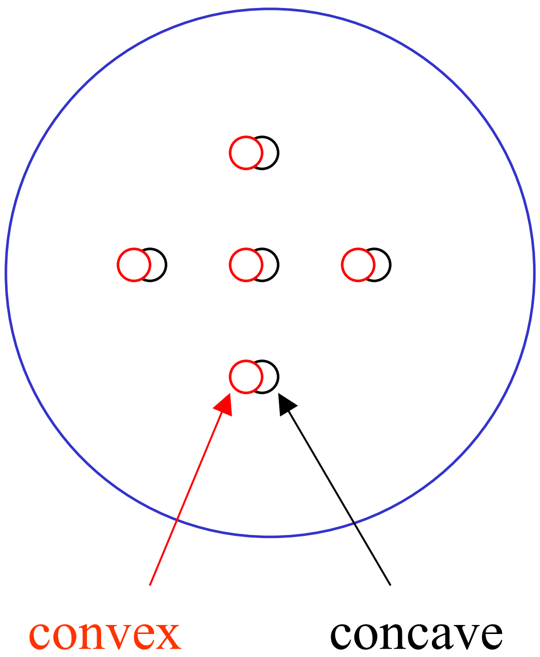
The required positions may be different from the target locations.

Problem of convex and concave alignment



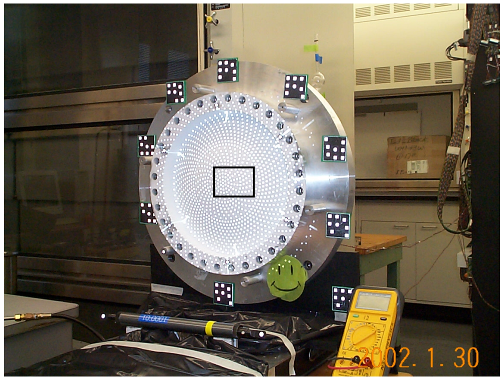


Problem of alignment

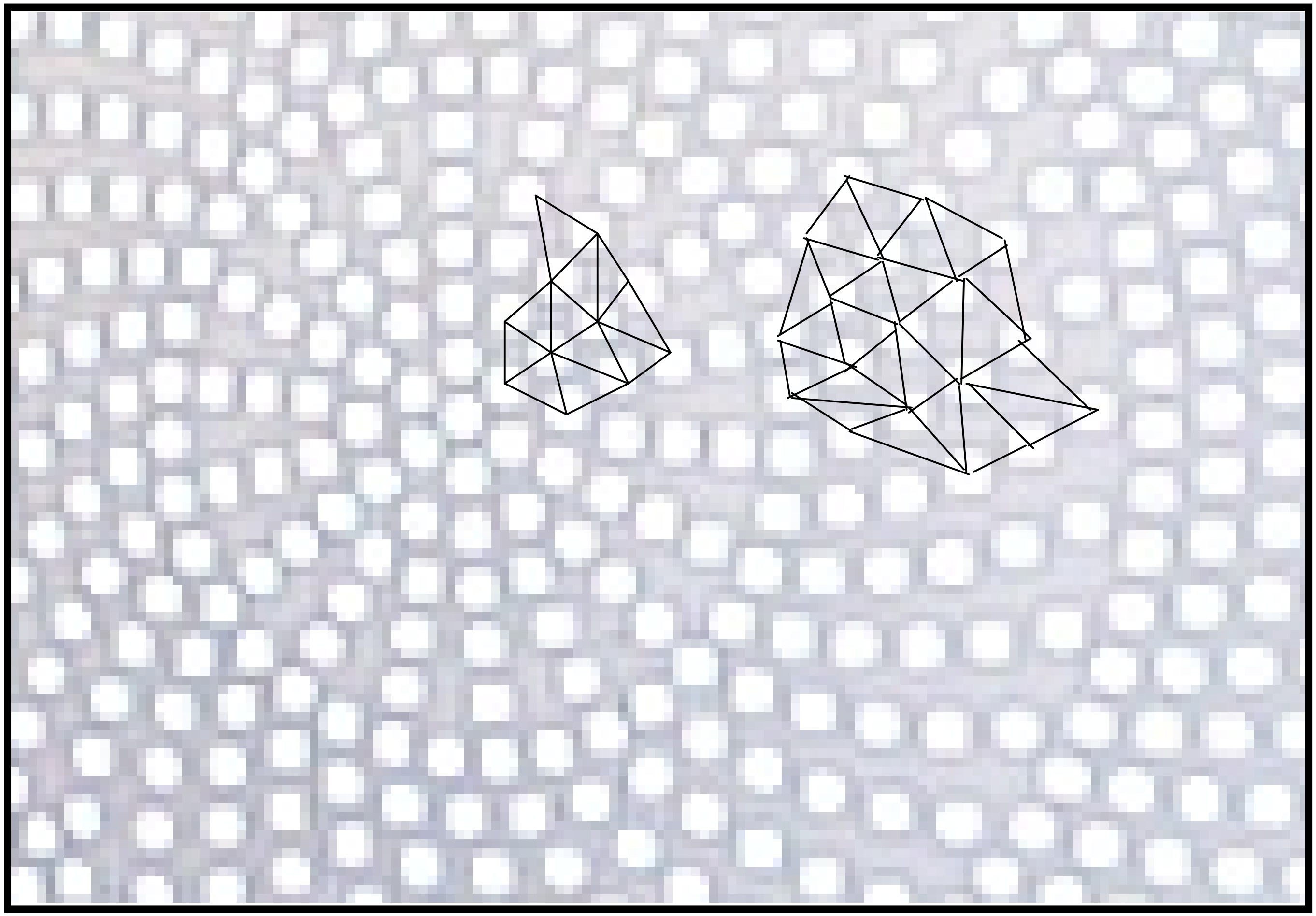


This makes it difficult to determine the window thickness

VANGO



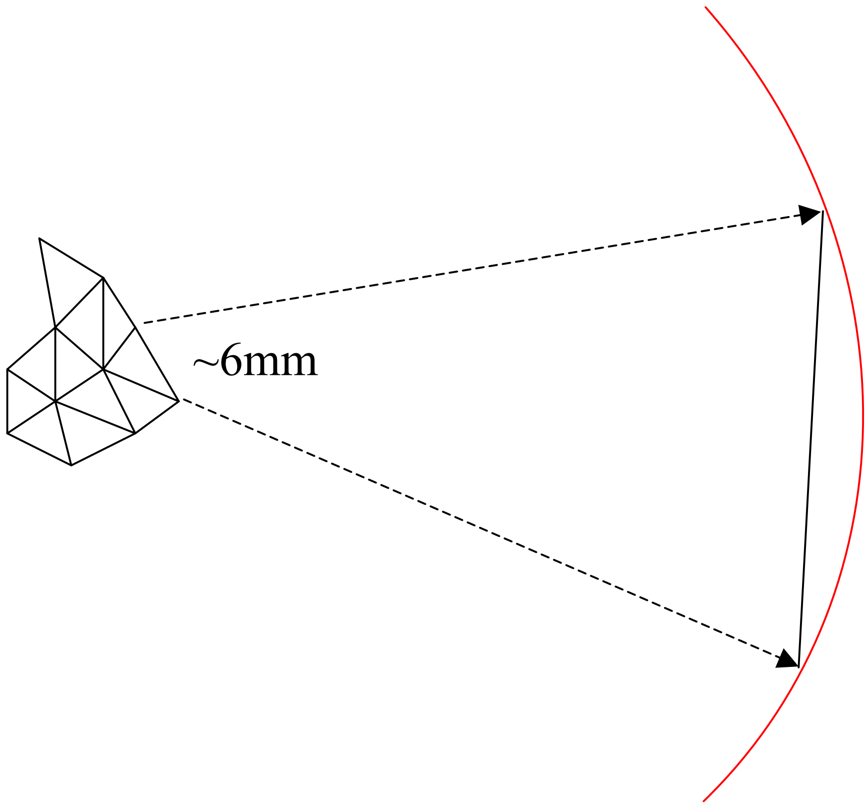
VANGO uses a TIN (Triangular Irregular Network) to create a surface model.



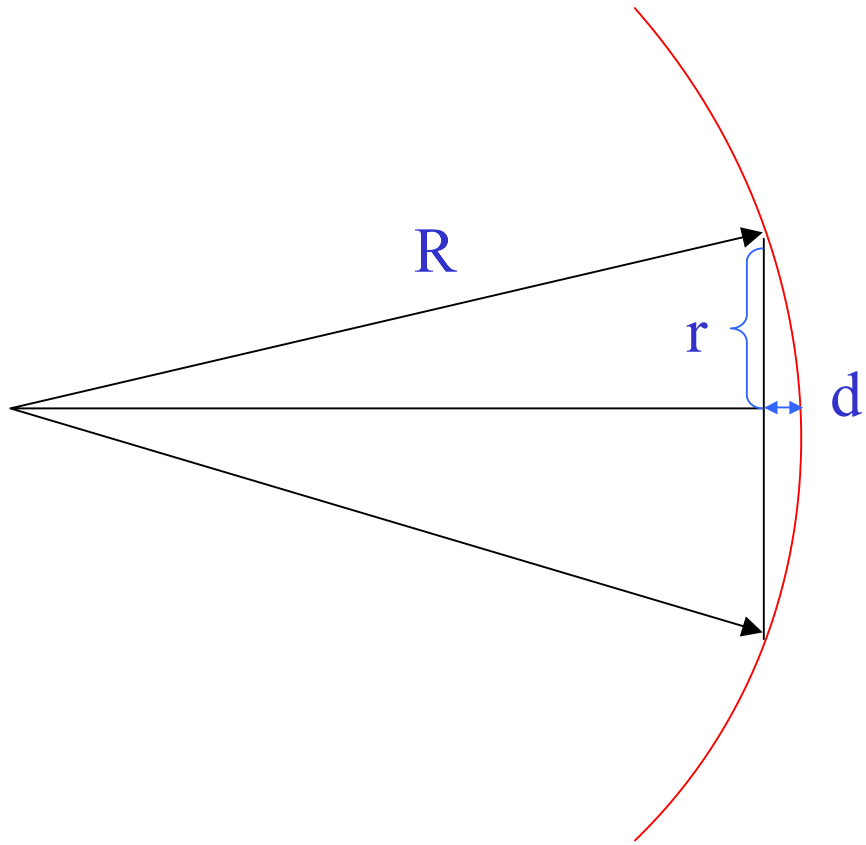
VANGO

Point on triangle is always < true point.

This is important to interpret any periodicities seen in the data; period of an oscillation caused by the TIN would be ~6mm



VANGO error

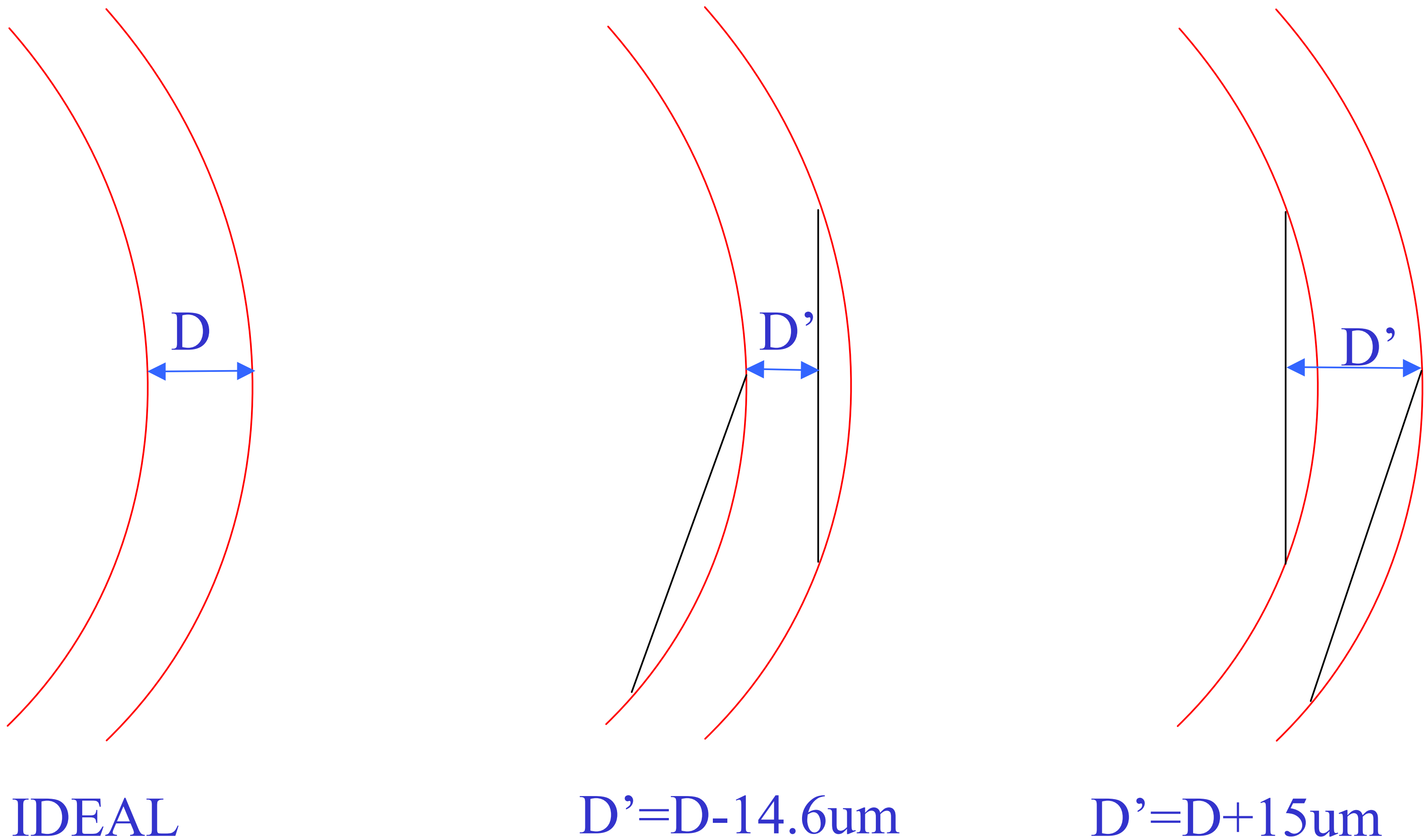


$$\frac{\theta}{2} = \sin^{-1}\left(\frac{r}{R}\right)$$

$$d = R - R\cos\left(\frac{\theta}{2}\right)$$

d = f(radius of curvature, size of triangle)

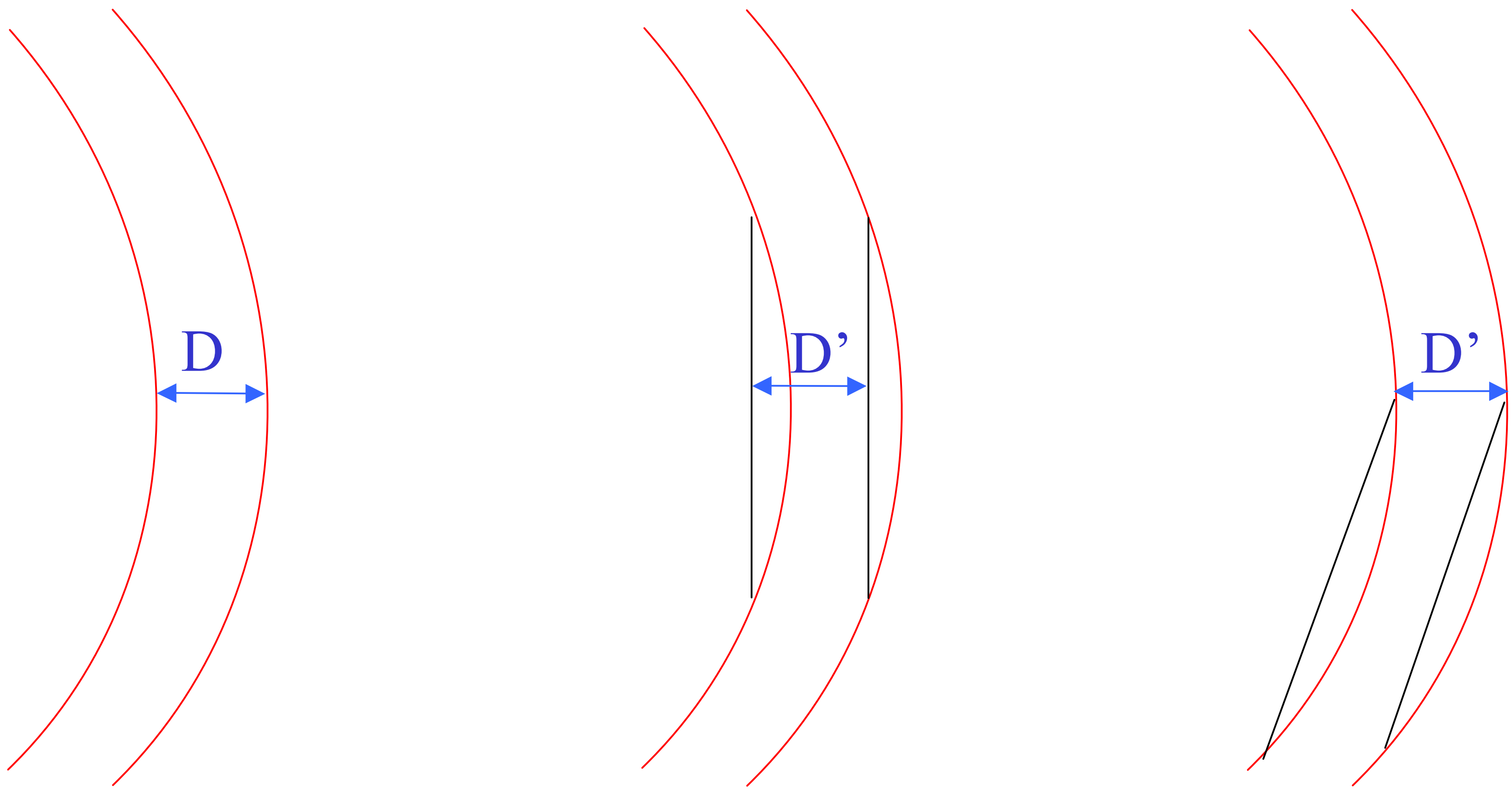
Errors in thickness due to VANGO TIN worst case geometry*



*Assumes 6mm chord and design radii 30.000cm and 30.844cm

Note: Nominal thickness (D) = 330um

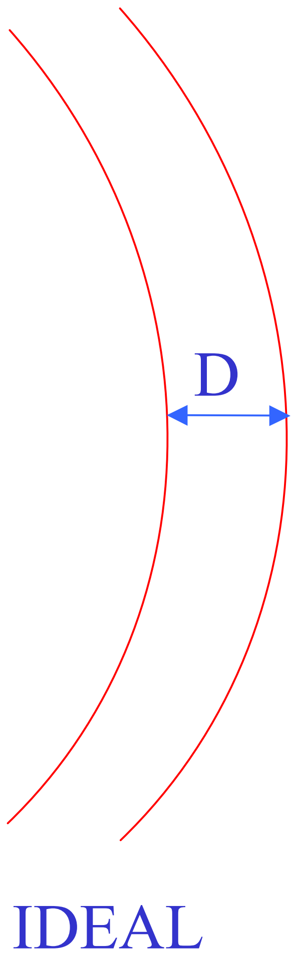
Errors in thickness due to VANGO TIN: intermediate and best case*

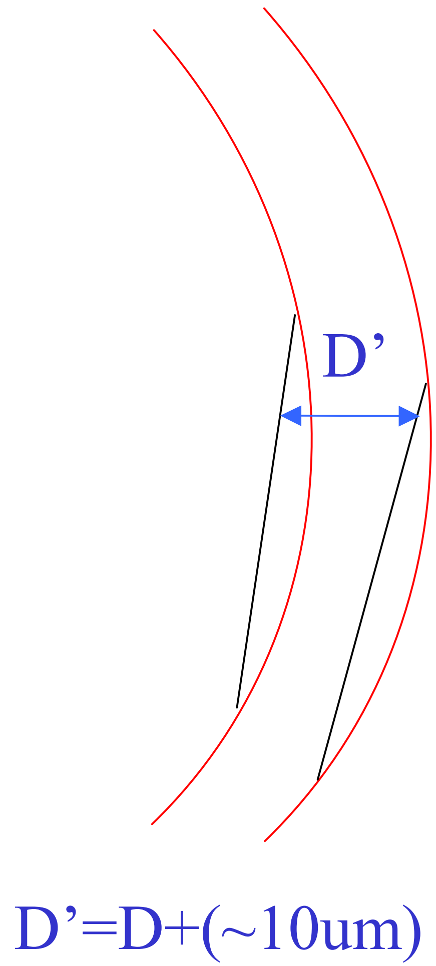


IDEAL　　D’=D-0.4um　　D’=D

*Assumes 6mm chord and design radii 30.000cm and 30.844cm　　Note: Nominal thickness (D) = 330um

TIN geometry for center of Window 4





VANGO TIN

Result *for the center:*

Thickness = 341.0um (± 5.5um) + (- ~10um)

Convex RMS = 3.6um   Concave RMS = 4.1um

The difference (thickness) should have an RMS of about 5.5um

VANGO error bars

Each point requires a unique error bar.

Error = f(phase between concave & convex triangles,
size of triangles,
radius of curvature)

Small patch sphere fit (SPSF)

Fit a sphere to the points near the point in question.

The sphere fit gives the equation of the sphere:

Small patch sphere fit (SPSF)

$$(x' - x)^2 + (y' - y)^2 + (z' - z)^2 = r^2$$

where x, y, z are unknowns

Solve for z choosing desired (x, y)

Do this for both concave and convex surfaces

The difference between $z_{concave}$ and z_{convex} is the thickness

Small patch sphere fit (SPSF)

To find the thickness at the center of the window,

solve for z choosing $x=0$ and $y=0$.

Small patch sphere fit (SPSF) errors

Intrinsic precision of the points used in the fit.

The basic assumption is that the intended shape was a sphere

Small patch sphere fit (SPSF)

Result *for the center*:

Thickness = 331.6um ± 5.5um

Error of spherical fit:
Convex RMS = 3.6um   Concave RMS = 4.1um
The difference (thickness) should have an RMS of about 5.5um

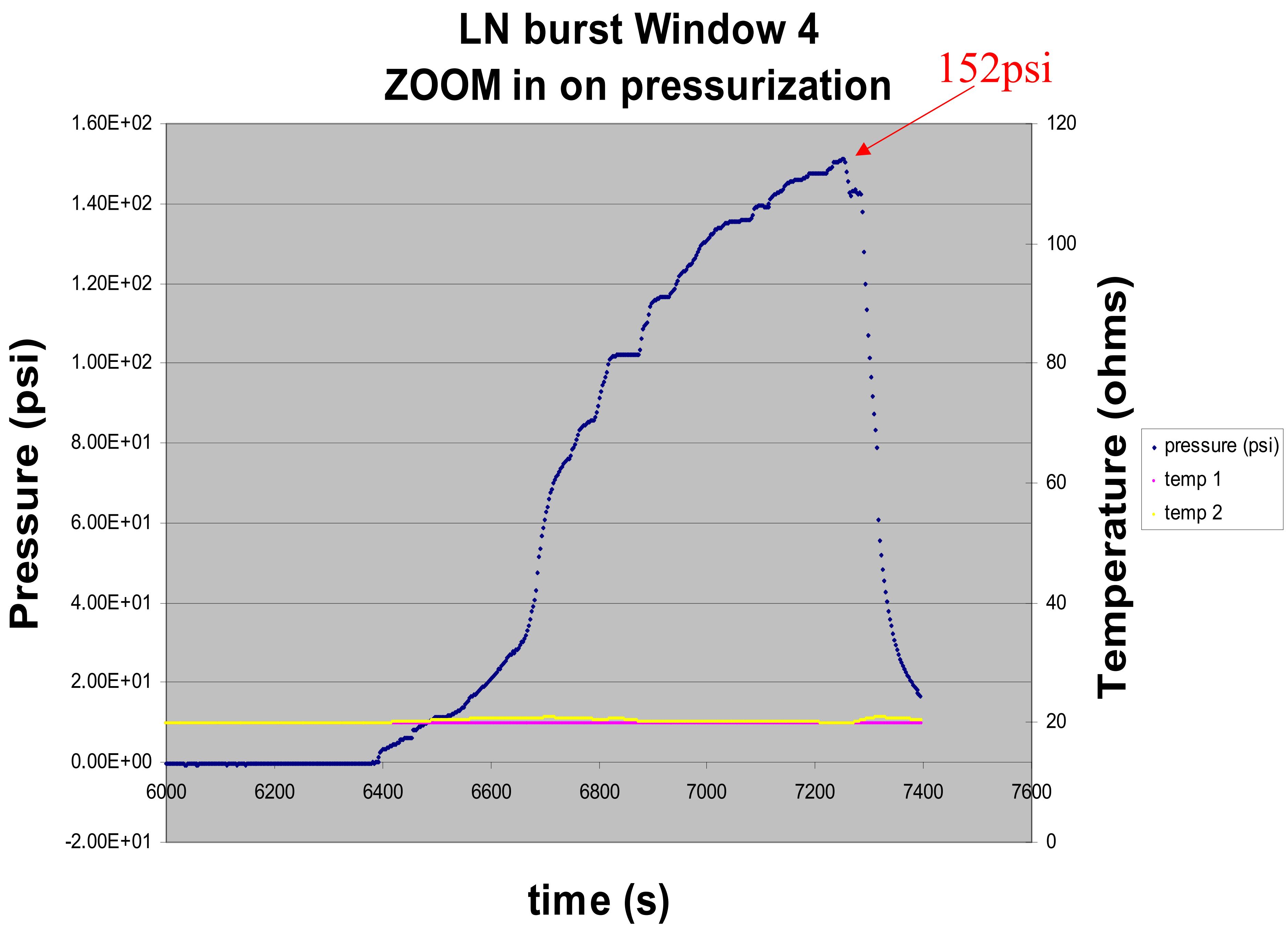
Summary of what we've done so far to determine thickness

Obtained two window thickness measurements *at the center*:

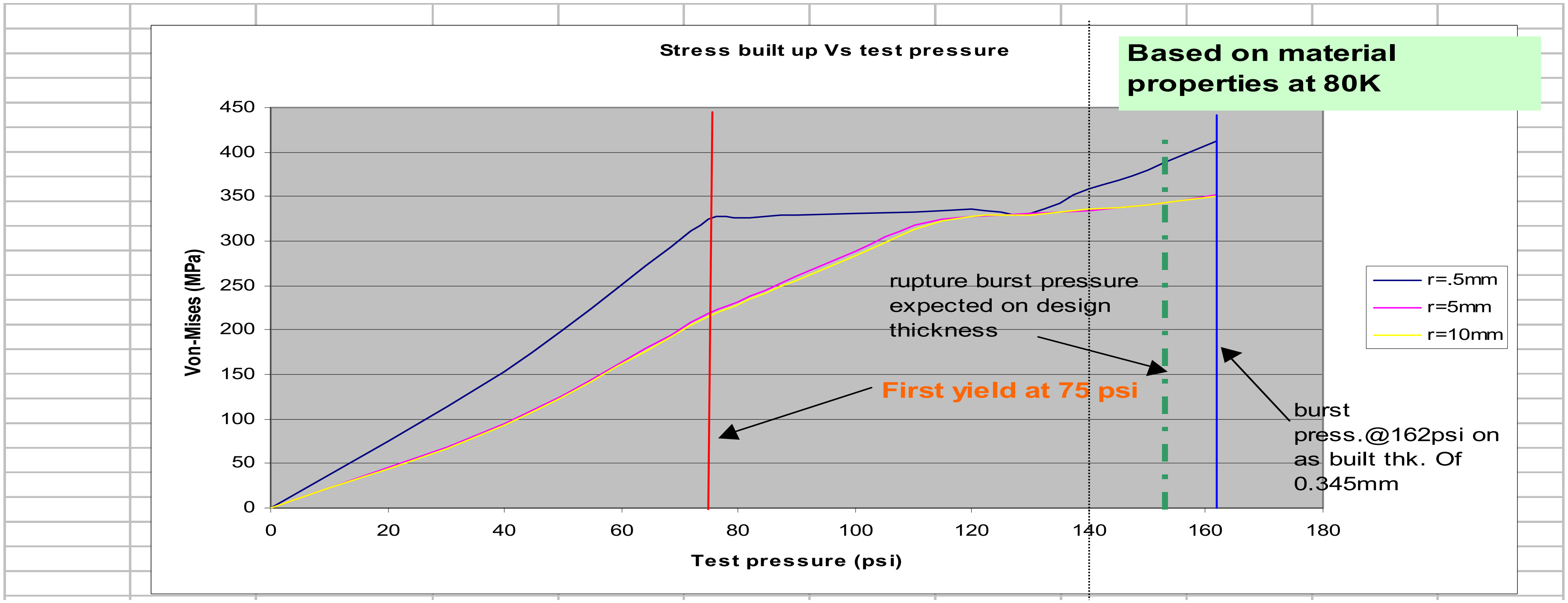
VANGO TIN 341.0um (±5.5um) + (- ~10um)

SPSF 331.6um ±5.5um

Additional support for the thickness value derived from SPSF:



LN burst Window 4
ZOOM in on pressurization
152psi
Pressure (psi)
1.60E+02
1.40E+02
1.20E+02
1.00E+02
8.00E+01
6.00E+01
4.00E+01
2.00E+01
0.00E+00
-2.00E+01
Temperature (ohms)
120
100
80
60
40
20
0
6000
6200
6400
6600
6800
7000
7200
7400
7600
time (s)
pressure (psi)
temp 1
temp 2



The predicted burst pressure (162psi) was greater than the observed burst pressure (152psi).

This implies that thickness assumed in the FEA (345um) was greater than the true thickness.

This would be consistent with a measured thickness of 331um.

What next?

We haven’t found the *thinnest* part of window yet,
only the thickness at a chosen point…which we chose to be the center.

How to find the thinnest point?

- Extended application of SPSF
  - Perform SPSF at many points and search for the minimum

- Modified TIN
  - Use a sphere to approximate the triangular surface between measured points