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Spatially Resolved Acoustic Spectroscopy: a laser ultrasonic technique for material characterisation

Wenqi Li, Jethro Coulson,Paul Marrow, Richard Smith, Matt Clark, Mike Somekh and Steve Sharples

Applied Optics Group, Electrical Systems & Optics Research Division
Faculty of Engineering, University of Nottingham.

wenqi.li@nottingham.ac.uk

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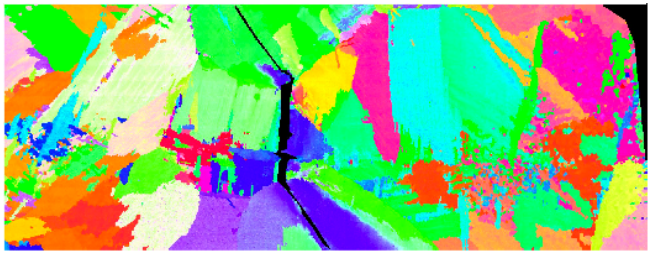
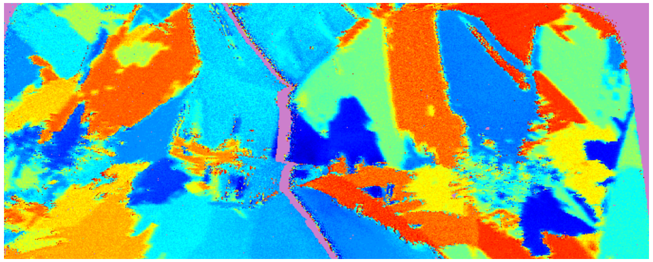
Part 1: Context.
What we measure, what it shows us

Context: laser ultrasonics for materials characterisation, including imaging microstructure

EBSD image courtesy of University of Wales, Swansea



SRAS surface acoustic wave velocity image



- **Ultrasonic** technique
- Pulsed laser excites surface acoustic waves (SAWs)
- They are detected using another laser close to the generation region
- Use SAW velocity – varies with grain orientation – as contrast mechanism
- Several important material properties are **structure sensitive:** e.g. yield strength, fracture toughness, thermal conductivity
- We don’t measure acoustic velocity directly, we use the acoustic spectrum of the SAWs, which changes with excitation efficiency. It is a localised measurement, hence “spatially resolved acoustic spectroscopy” – SRAS for short

SRAS and EBSD: similarities and differences (1)*

- Both are **scanning** techniques – single point measurement, repeated many times to make a picture (not "full field")

- EBSD has (and always will have) much better **spatial resolution**
  - Best SRAS resolution so far is **25μm**, potentially ~2-10μm without getting too exotic
  - **Typical SRAS resolution: 50-100μm**

- SRAS can give **quantitative** orientation information
  - Getting quite fast now, limited to materials we know the elastic constants of (Al, Ni, Inconel, stainless steel)

- SRAS is pretty fast – routinely able to scan at **1000 points/sec**
  - 10,000 points/sec or more is very feasible

*EBSD = electron backscatter diffraction, a scanning electron microscope technique

SRAS and EBSD: similarities and differences (2)*

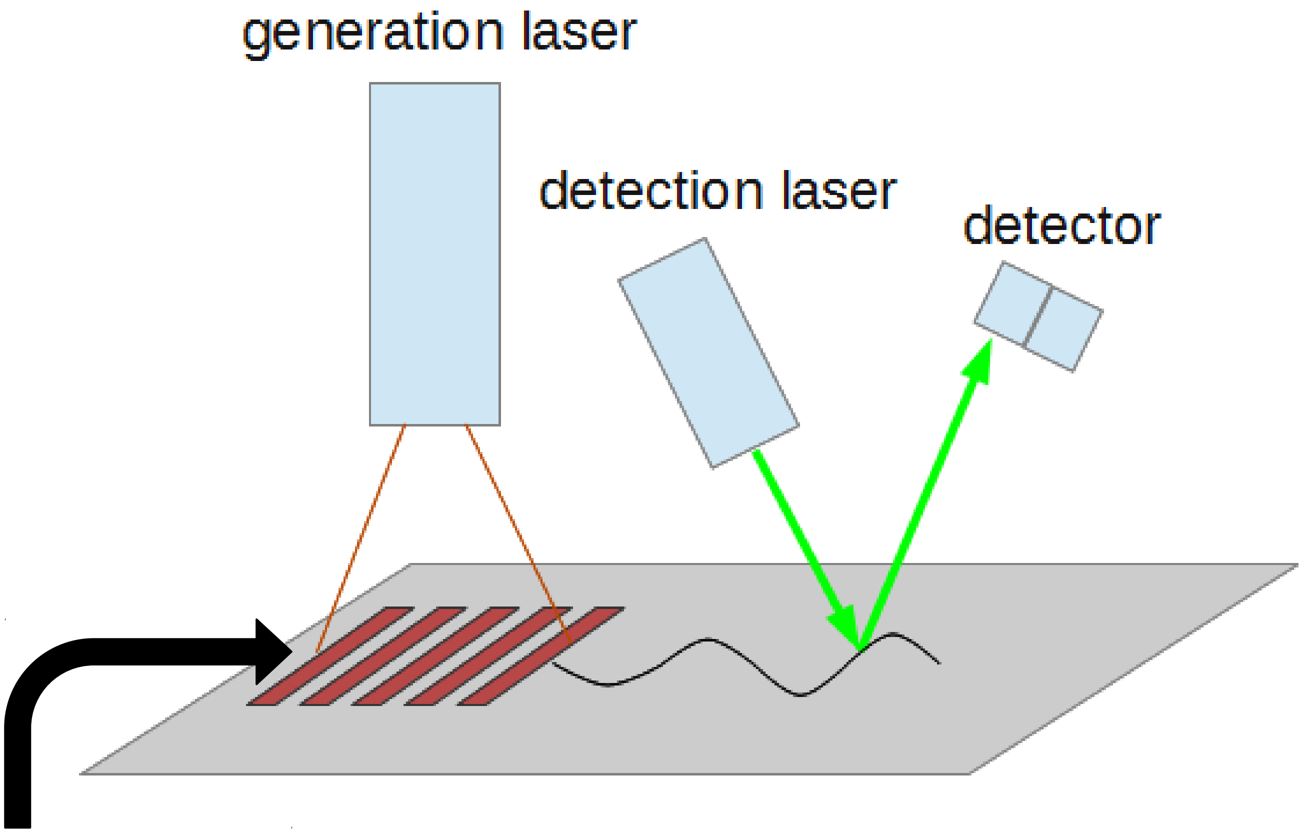
- SRAS does **not** require samples to be **polished**
  - The surface roughness limit is that SAWs must be able to propagate a short distance
  - Can “see” below thin coatings (e.g. oxide layer)
- SRAS can be used on **any sized sample**, and does not require a vacuum
  - Limited only by the scanning stages / gantry
  - Entirely noncontact
  - Non-metalic/non-conductive is not a problem
- So…: SRAS and EBSD are ***complementary* techniques**

*EBSD = electron backscatter diffraction, a scanning electron microscope technique

Part 2: SRAS theory and Instrumentation.

- Some already know how it works
- I will give a quick introduction here, but if you’re interested in learning more I can have a chat with you over the coffee break if you’re interested

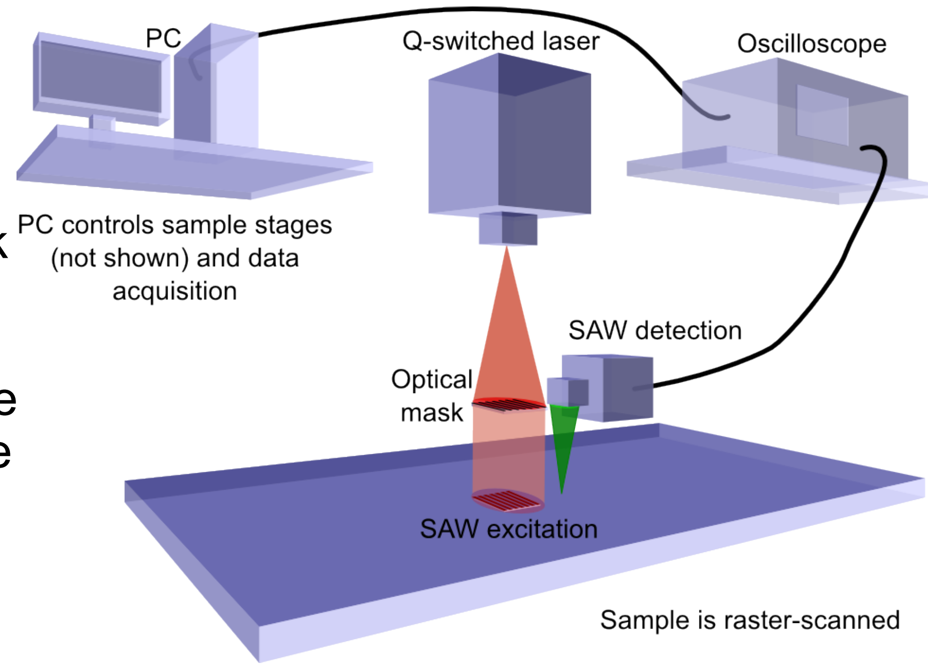
Laser ultrasonics: the essentials

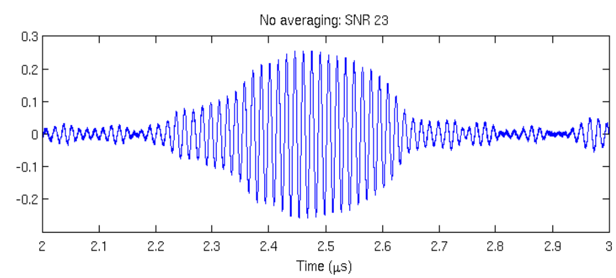


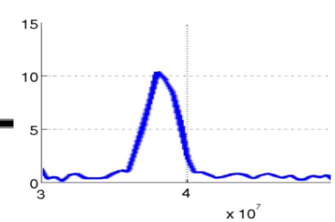
- **The size of this grating patch defines your resolution**
- **The direction of the lines defines the direction of wave propagation**

SRAS theory: instrumentation

- Q-switched laser fires a single sharp pulse 1000 times a second, which covers a broad frequency spectrum
- Pass laser beam through optical mask which is a grating
- Because we use a grating to excite the SAWs, we only generate SAWs of one specific wavelength, *λ* (the grating spacing)
- Grating acts as a filter: the frequency (*f*) of the SAWs generated is determined by fringe spacing (*λ*) and SAW velocity (*v*), provided that the frequency is within the bandwidth of the laser: ***v = f λ***
- SAWs are detected a short distance away using another laser

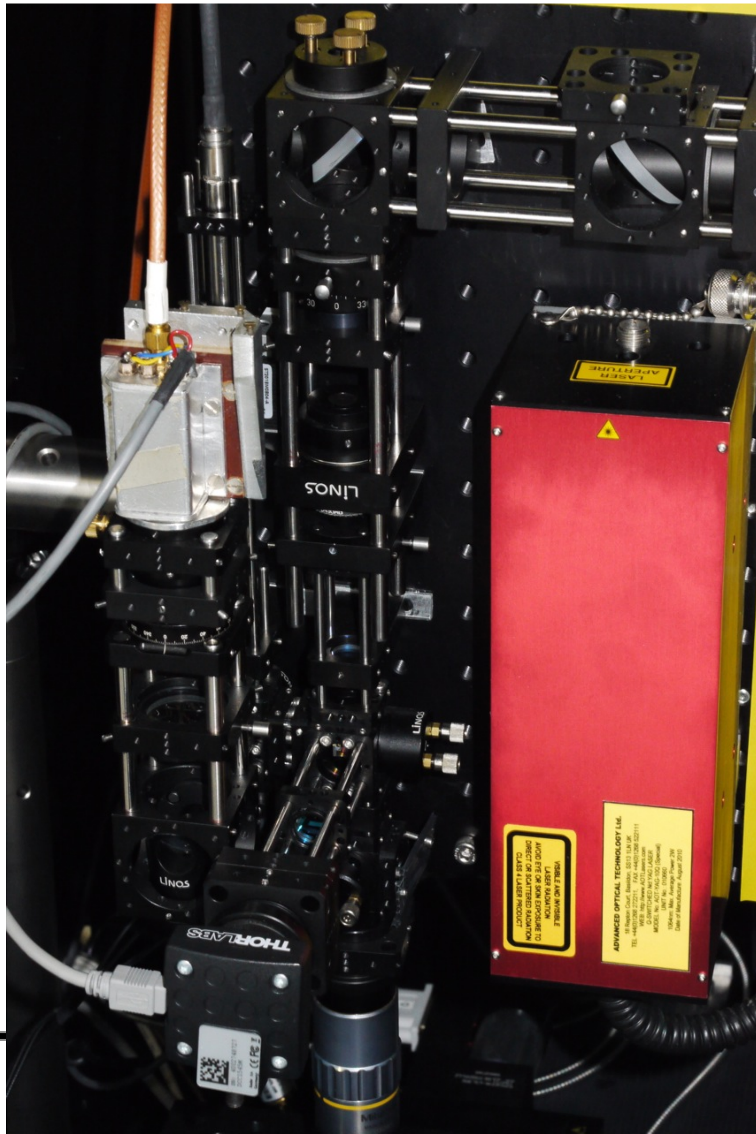


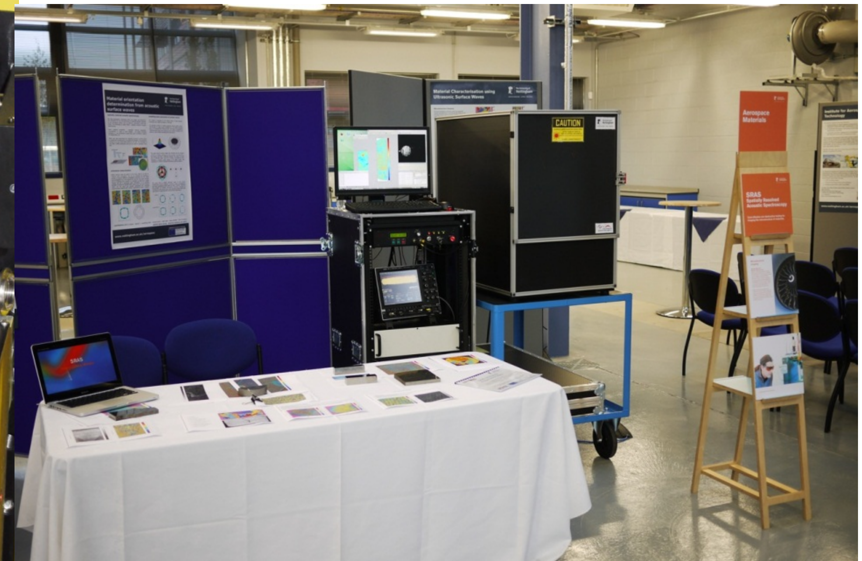




2012: third generation instrument "emda SRAS system"

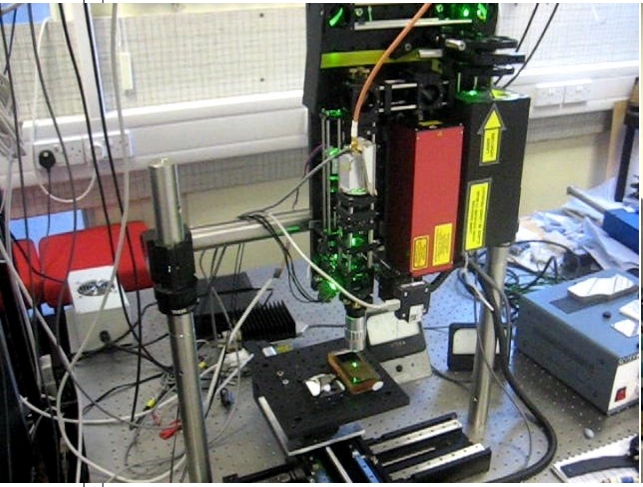
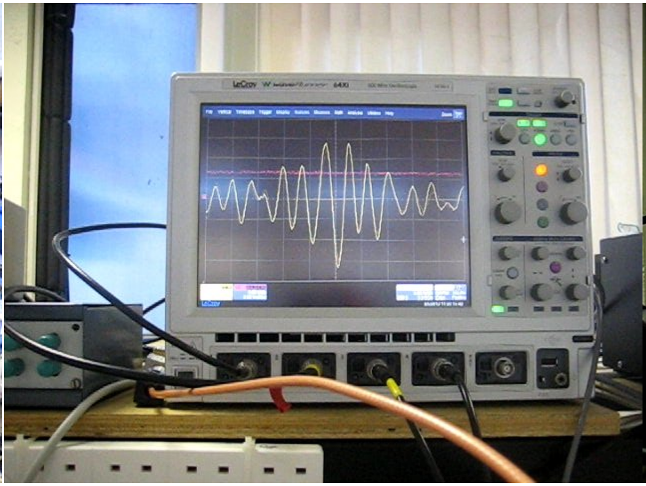
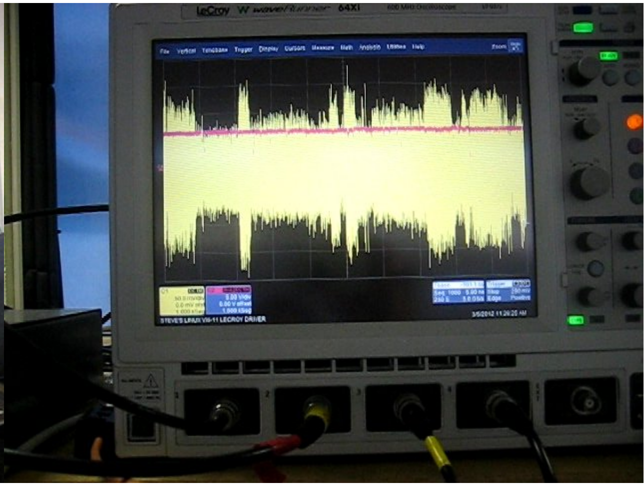
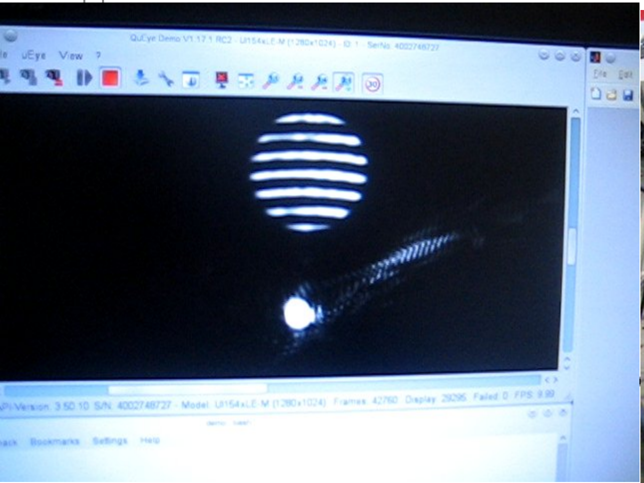
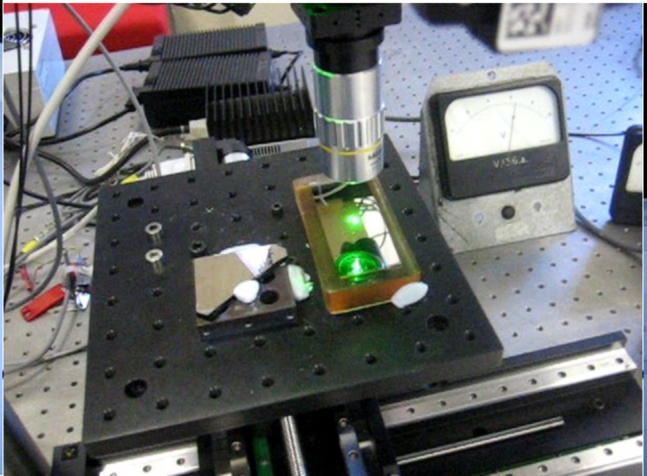
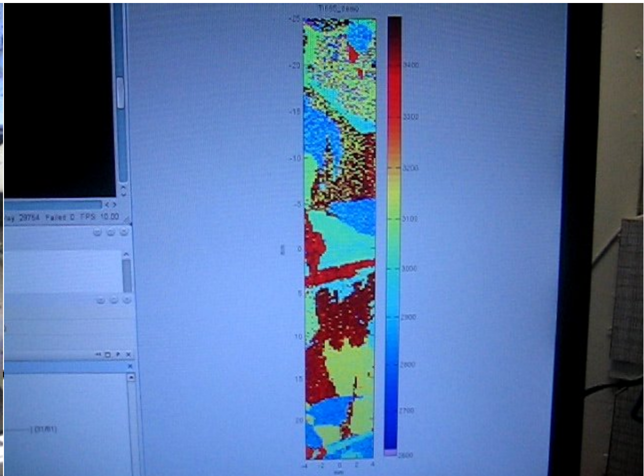
- Aerospace Technology Centre launch event, 25-26 October 2012





Scanning a sample

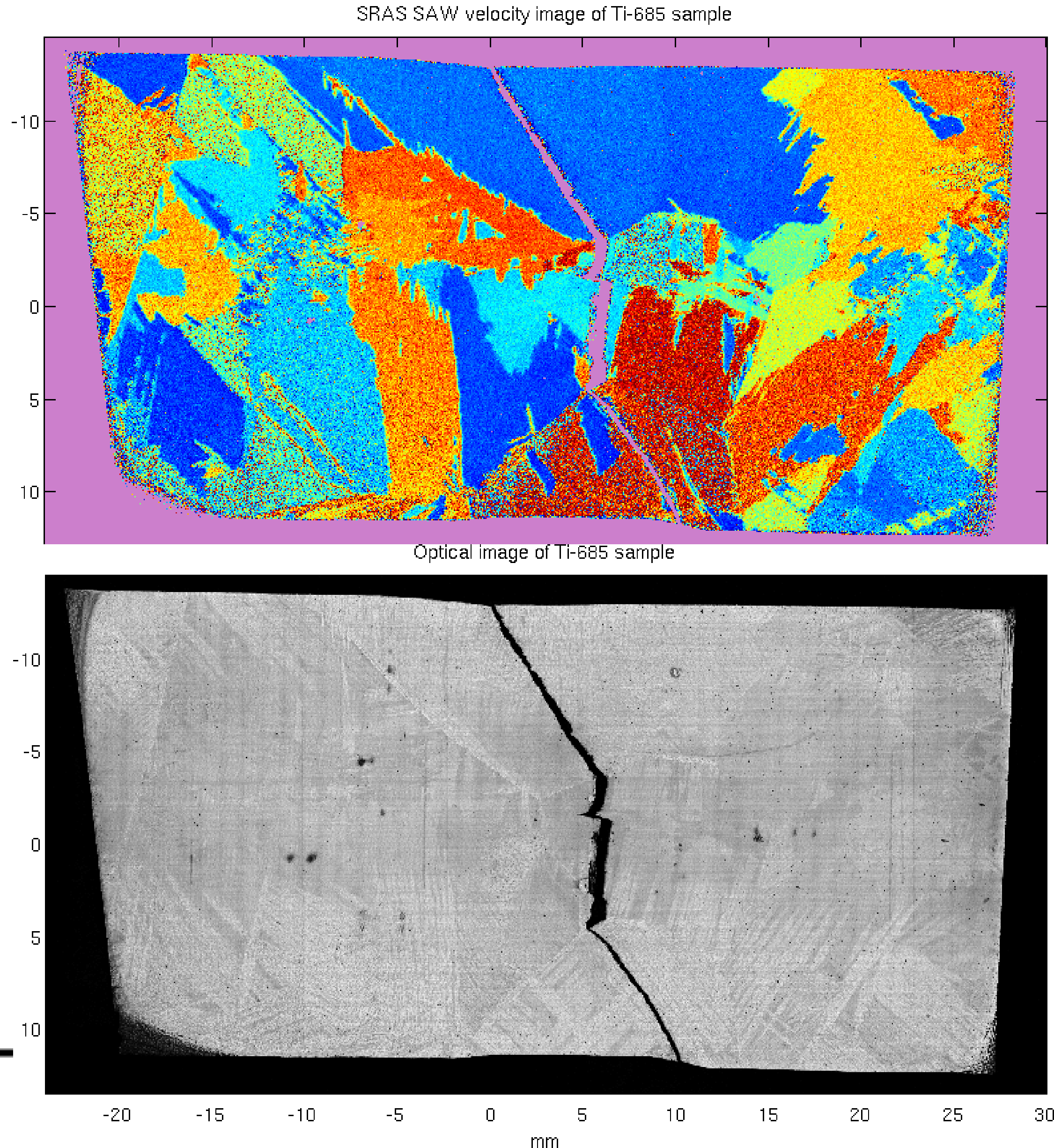
- Link to scanning movie

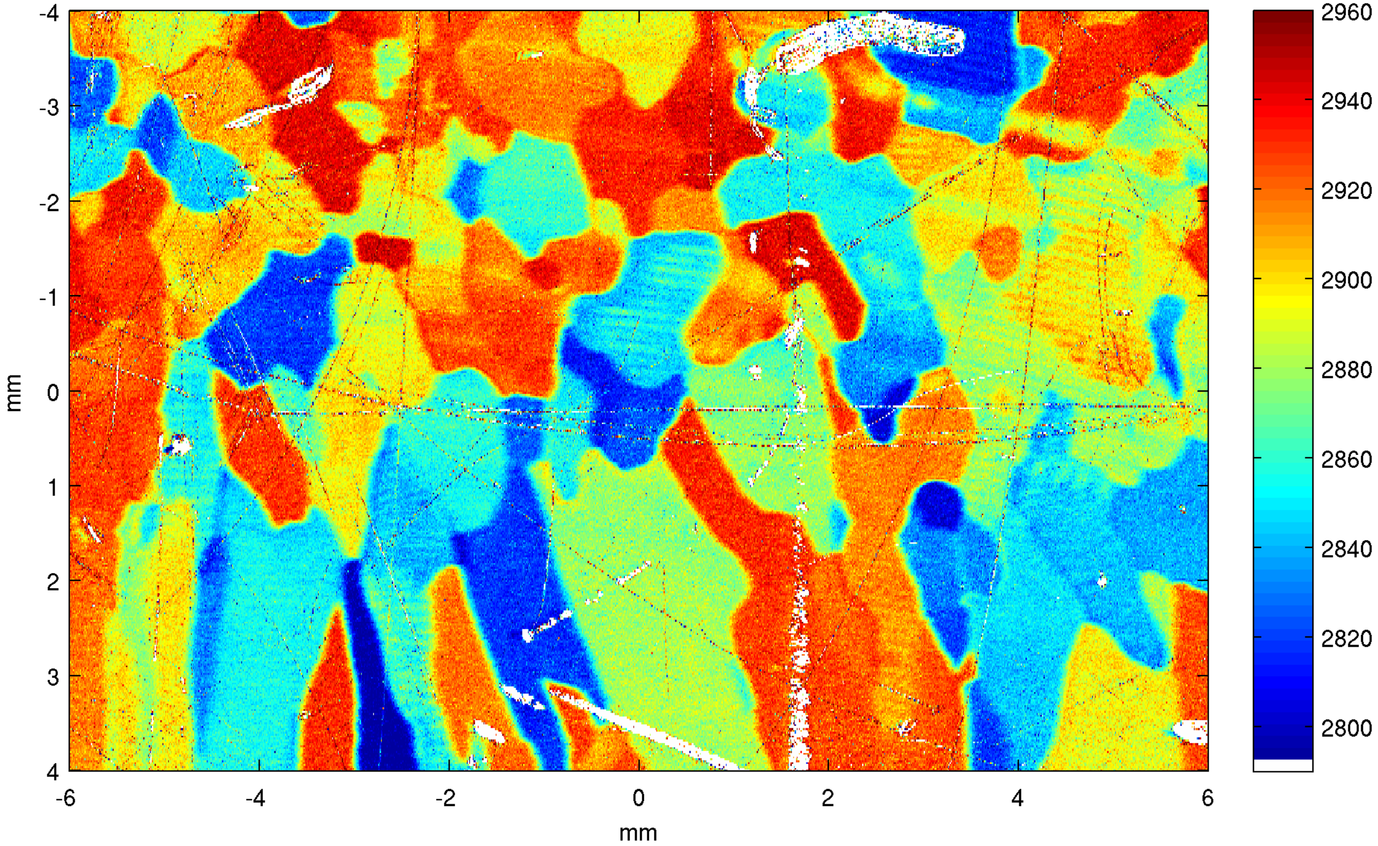
Part 3: Showing off.
Some example SRAS velocity images

Ti-685

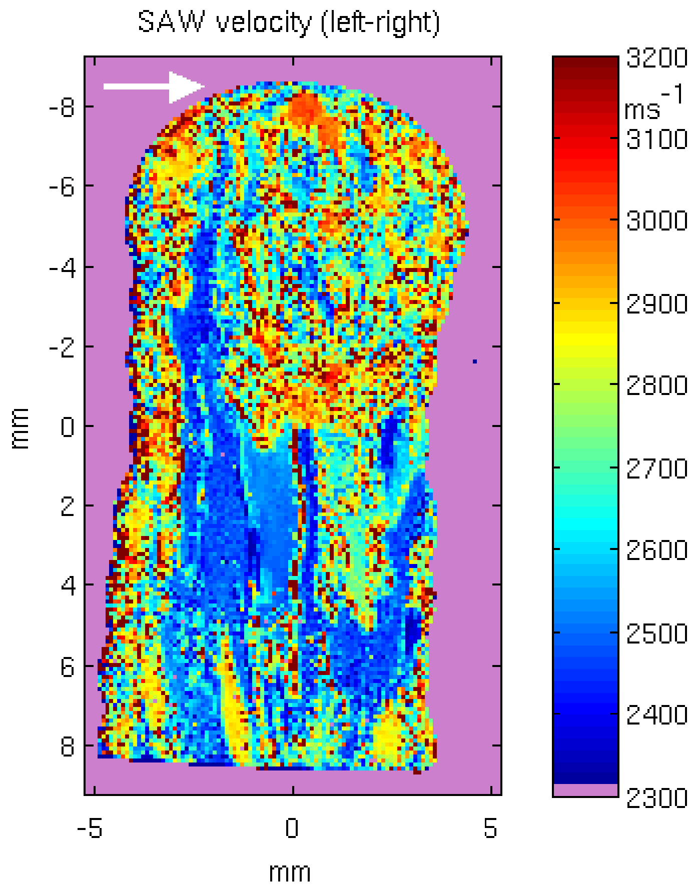
- Ti-685
- 54x28mm
- 8x50μm pixel size
- 3.8 megapixels
- 52 minutes scan time
- >1200 points/sec
- Pictures here do not really do it justice

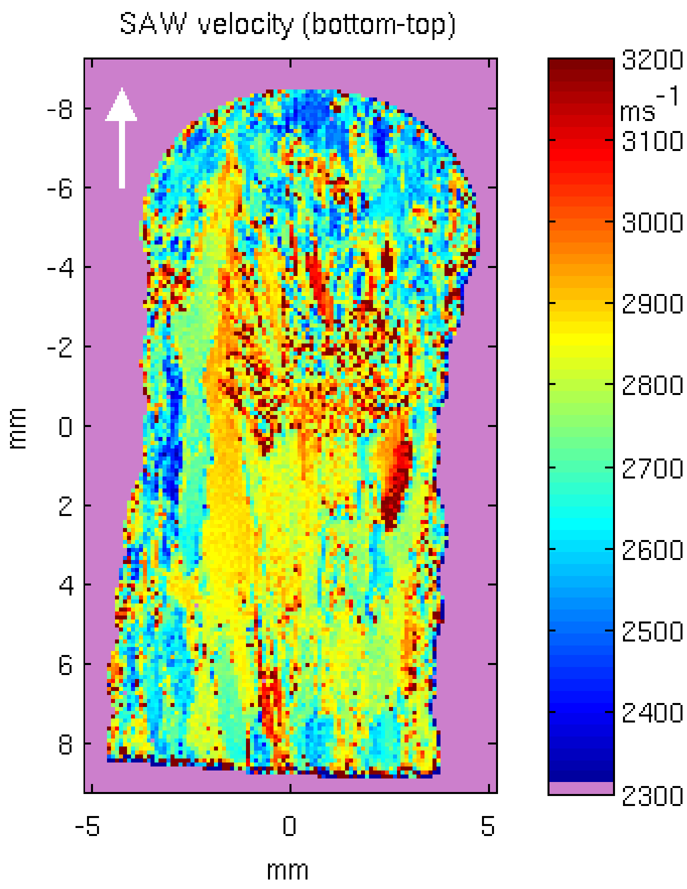


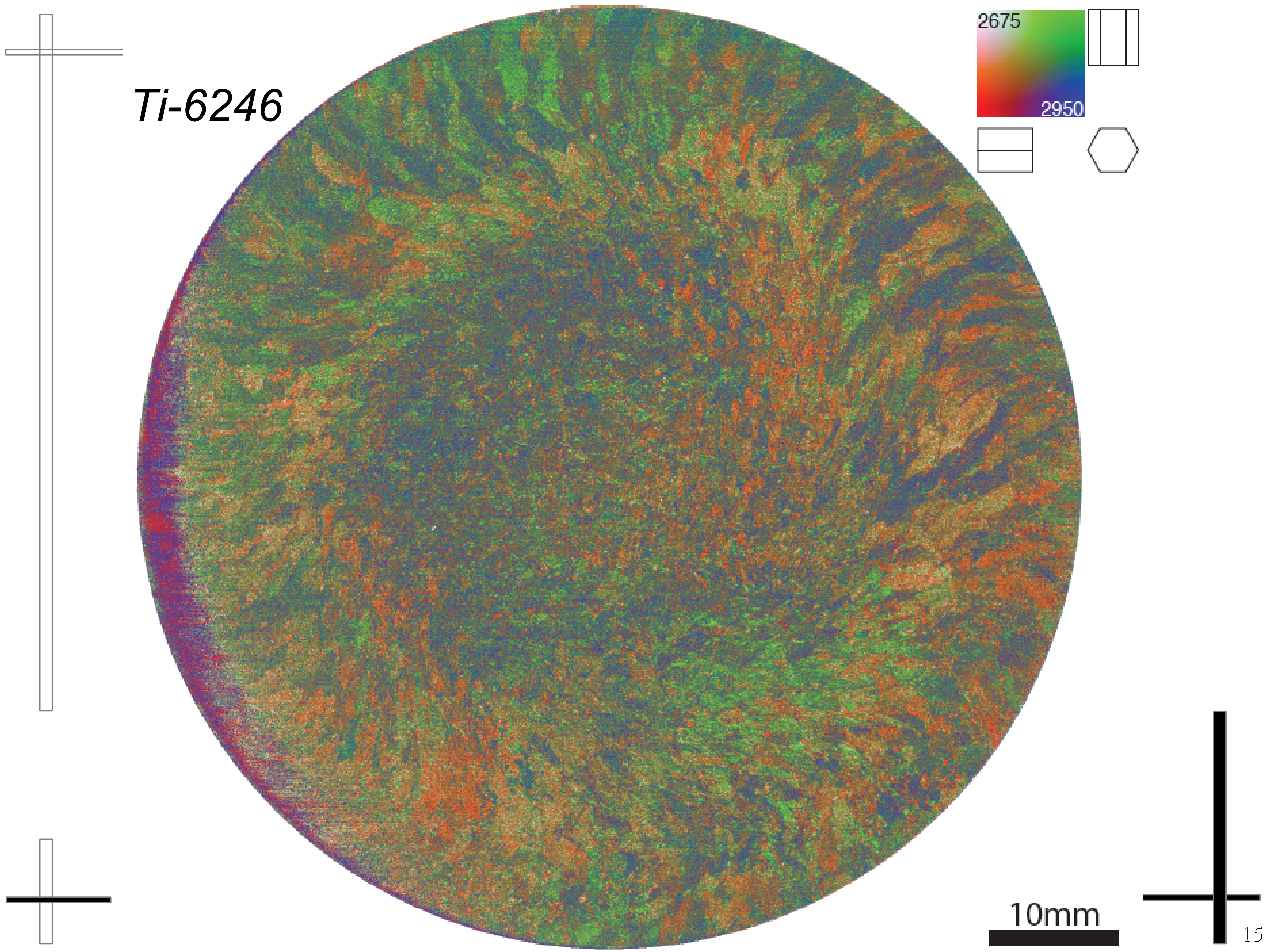
Large grain aluminium



Waspaloy Wire + Laser (Nottingham, 2007)





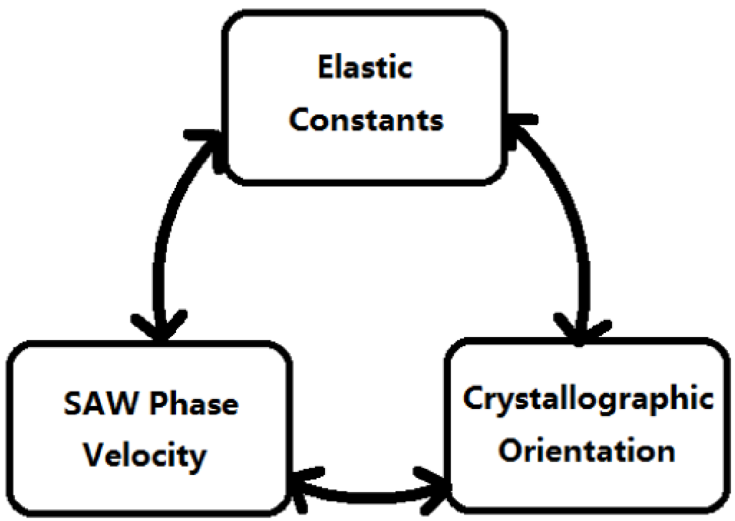

Ti-6246
2675
2950
10mm

Part 4: Beyond SAW velocity. Crystallographic orientation

Data processing – orientation determination

- There is a causal relationship between:
  - (1) a material's **mechanical properties and elastic constants** (ρ, C_{ijkl} etc)
  - (2) the **crystallographic orientation**,
  - (3) the **SAW velocity** (in multiple directions on a given plane)

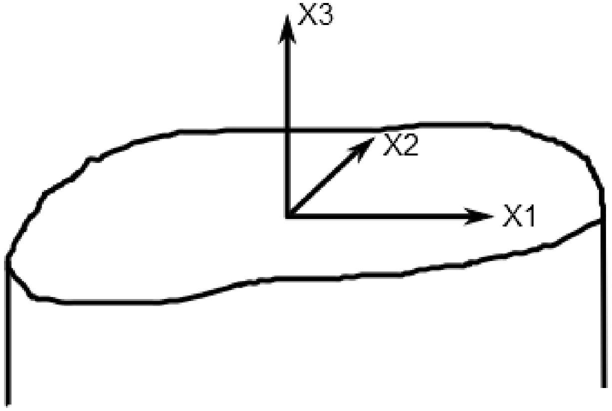
- If you know 2 of these things, you can work out the 3rd:
  - For many years (2) and (3) have been used to determine (1)
  - The "forward problem" is where we know (1) and (2), and calculate (3)
    - Done using numerical technique…:



Forward model: calculating SAW velocities from known orientation and known elastic constants

Wave equation:

$$\rho \frac{\partial^2 u_j}{\partial t^2} = \frac{\partial T_{ij}}{\partial x_i}, \ (i,j=1,2,3)$$



Boundary condition:

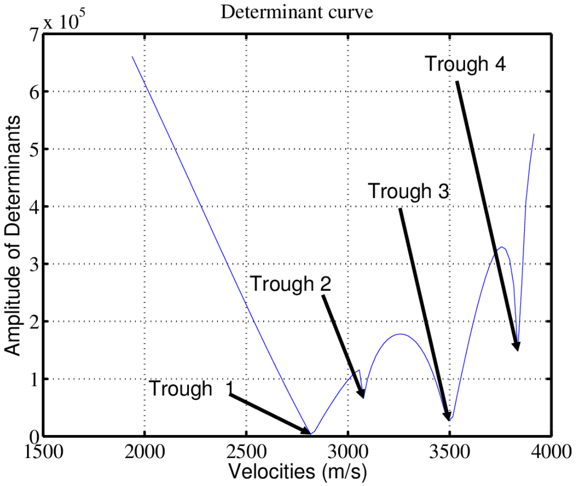
$$T_{3j} = c_{3jkl}\partial u_k/\partial x_l = 0, \ \text{for } j=1,2,3.$$

Solution of the wave equation:

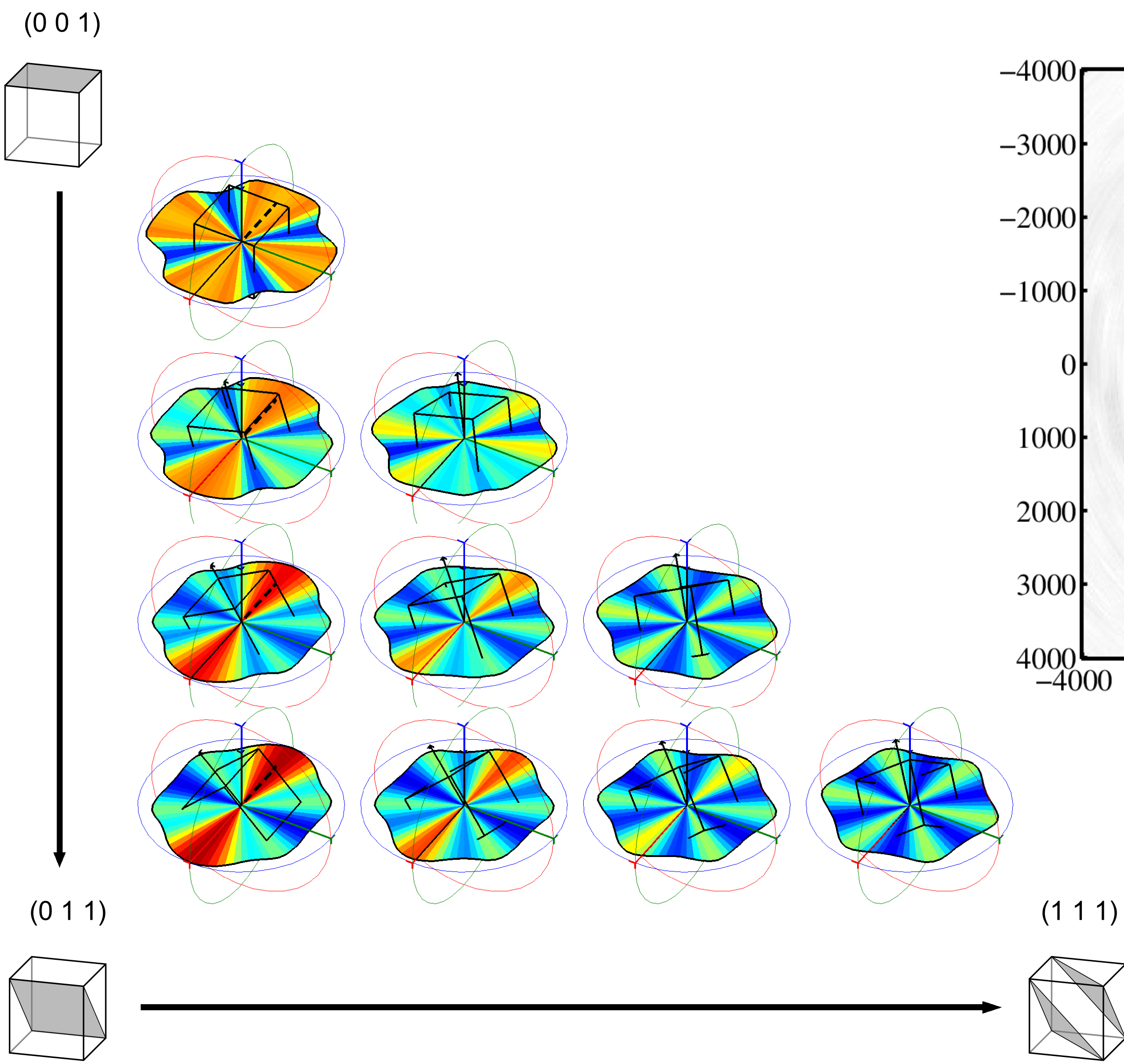
$$u_i = \sum_{n=1}^{3} C_n \alpha_i^{(n)} \exp[-j\beta l_3^{(n)} x_3] \exp[j(\omega t - \beta l_1 x_1 - \beta l_2 x_2)]$$

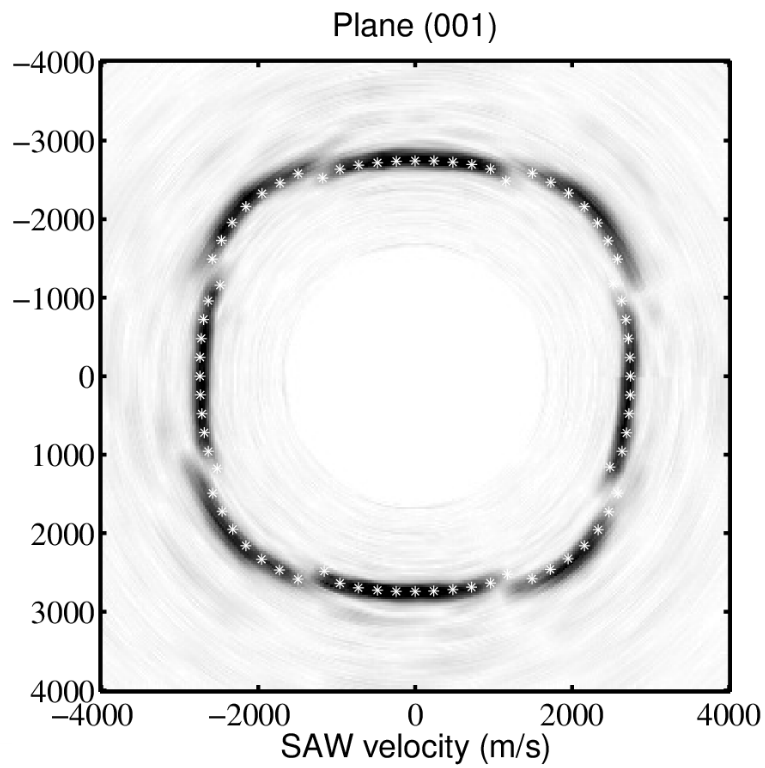
Determinant of the boundary condition:

$$d_{mn} = c_{m3kl}\alpha_k^{(n)} l_l^{(n)} = 0, \ \text{with } l_1^{(n)} \equiv l_1, \ l_2^{(n)} \equiv l_2.$$



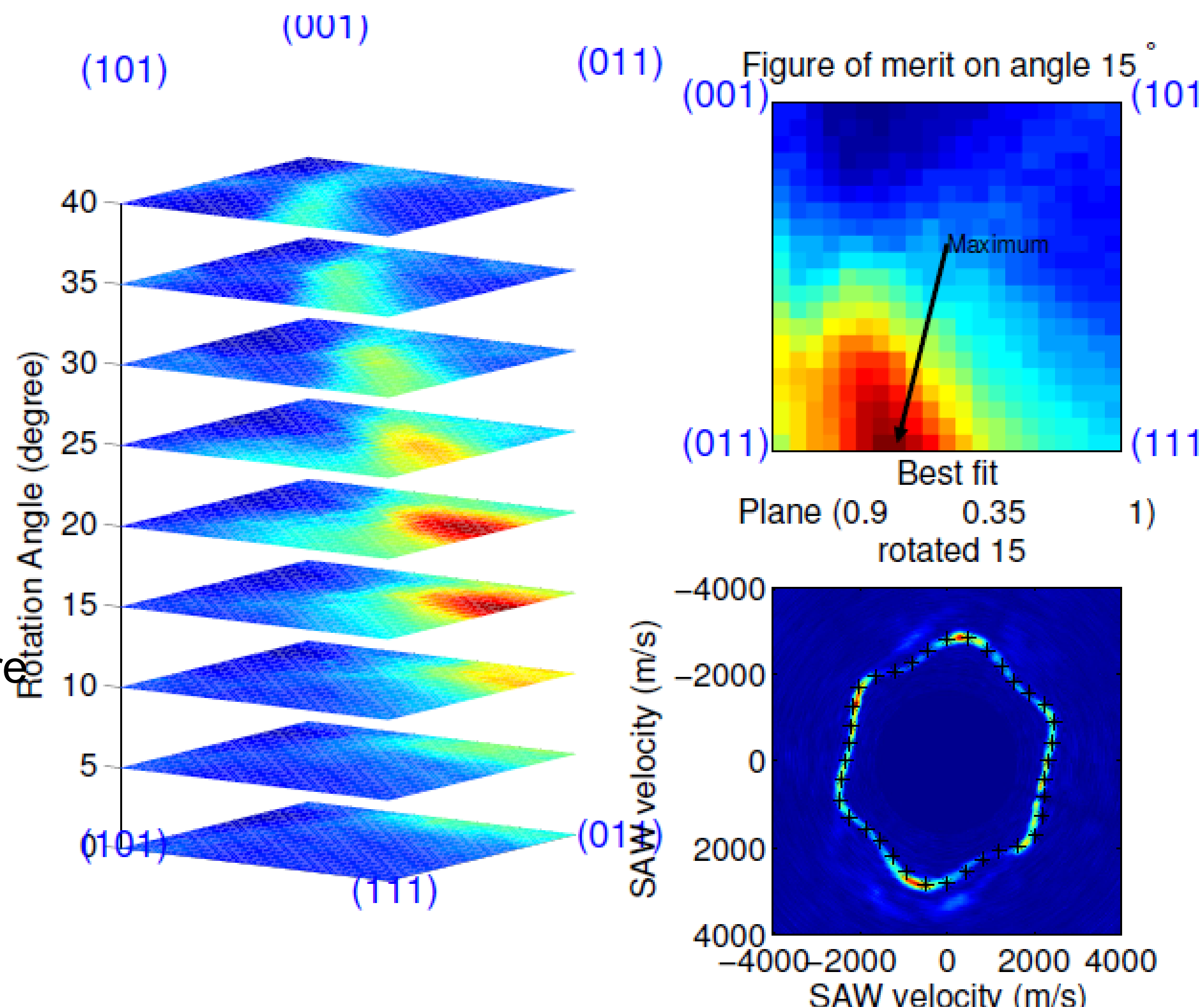
Example of calculating the SAW velocities for known orientations of cubic crystal: Nickel





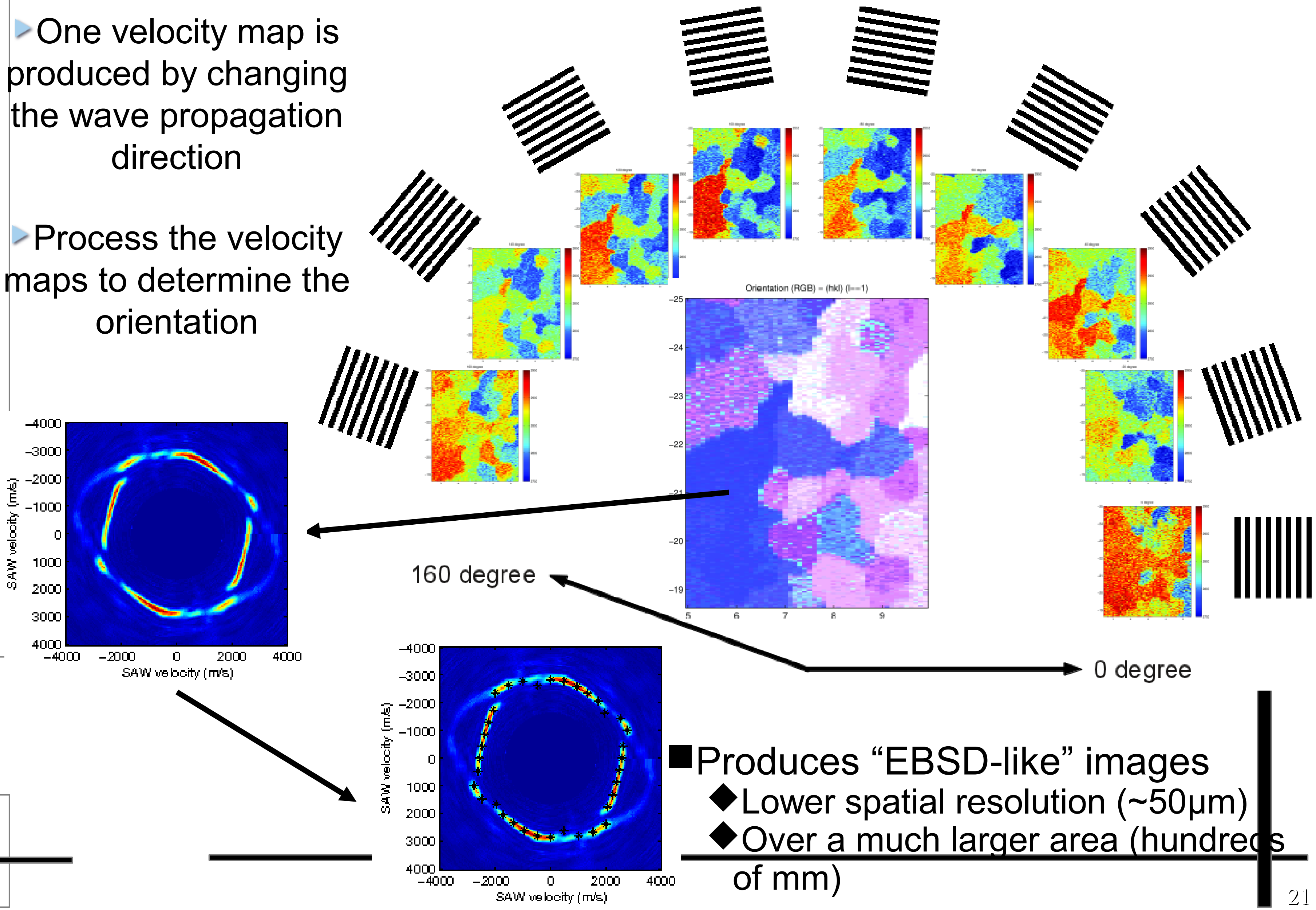
Orientation determination – for example, Nickel

- The forward model predicts the SAW velocities in all directions on all planes
- We see how well the experimentally measured velocity, in several propagation directions, matches the model
- This gives us a figure of merit for all planes and all rotations
- We choose the biggest figure of merit
- Simple! And getting faster…



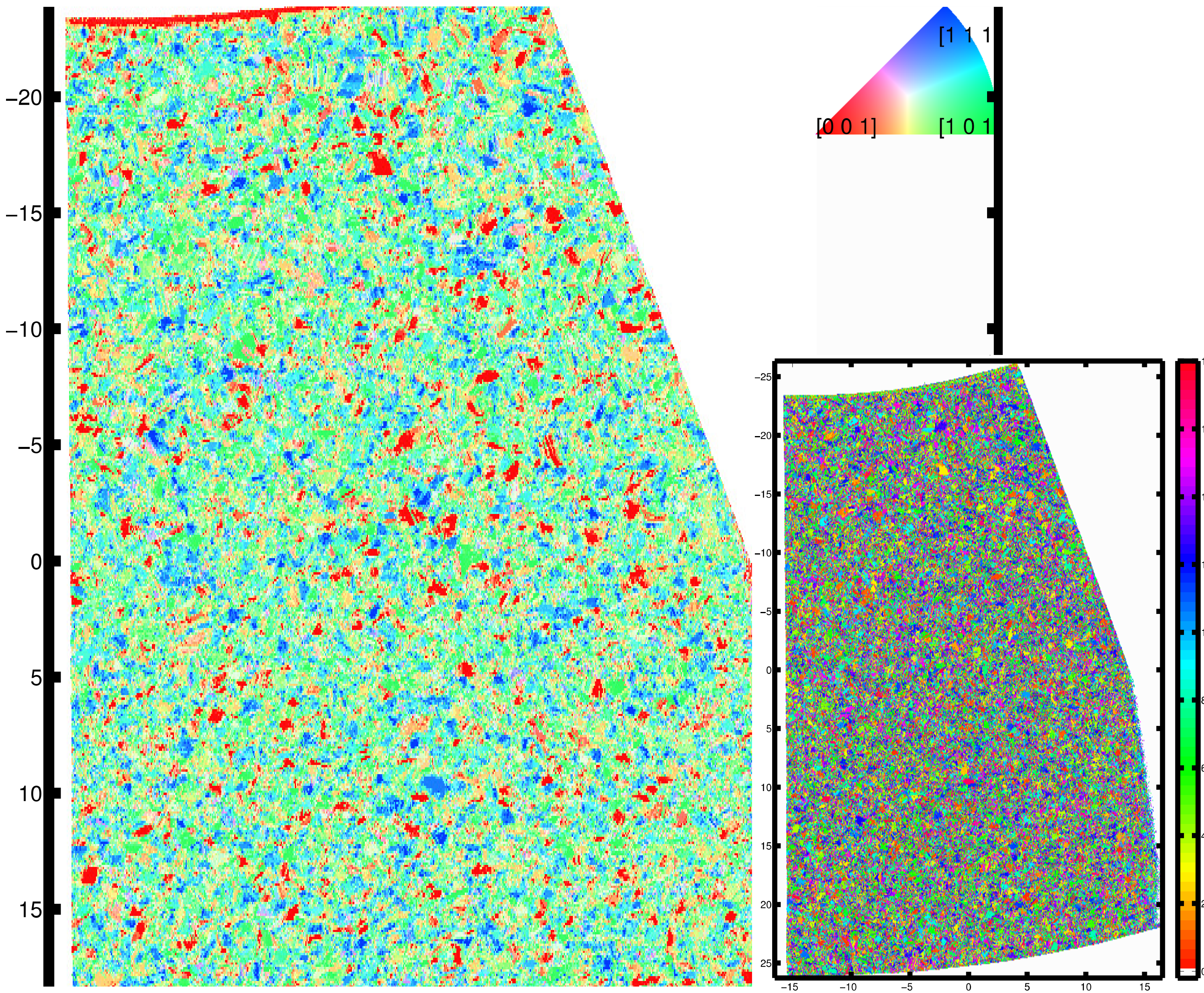
Orientation imaging - Aluminium

- One velocity map is produced by changing the wave propagation direction
- Process the velocity maps to determine the orientation

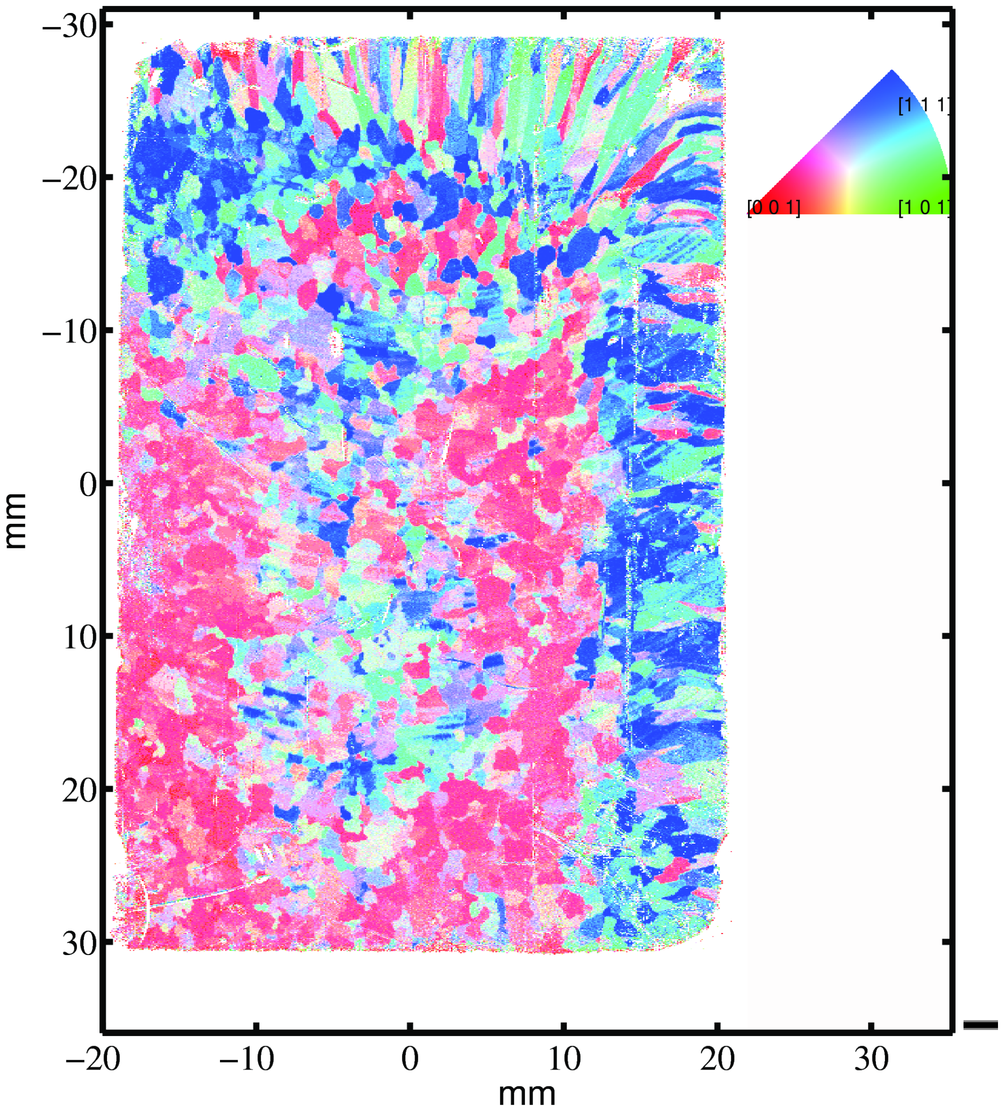


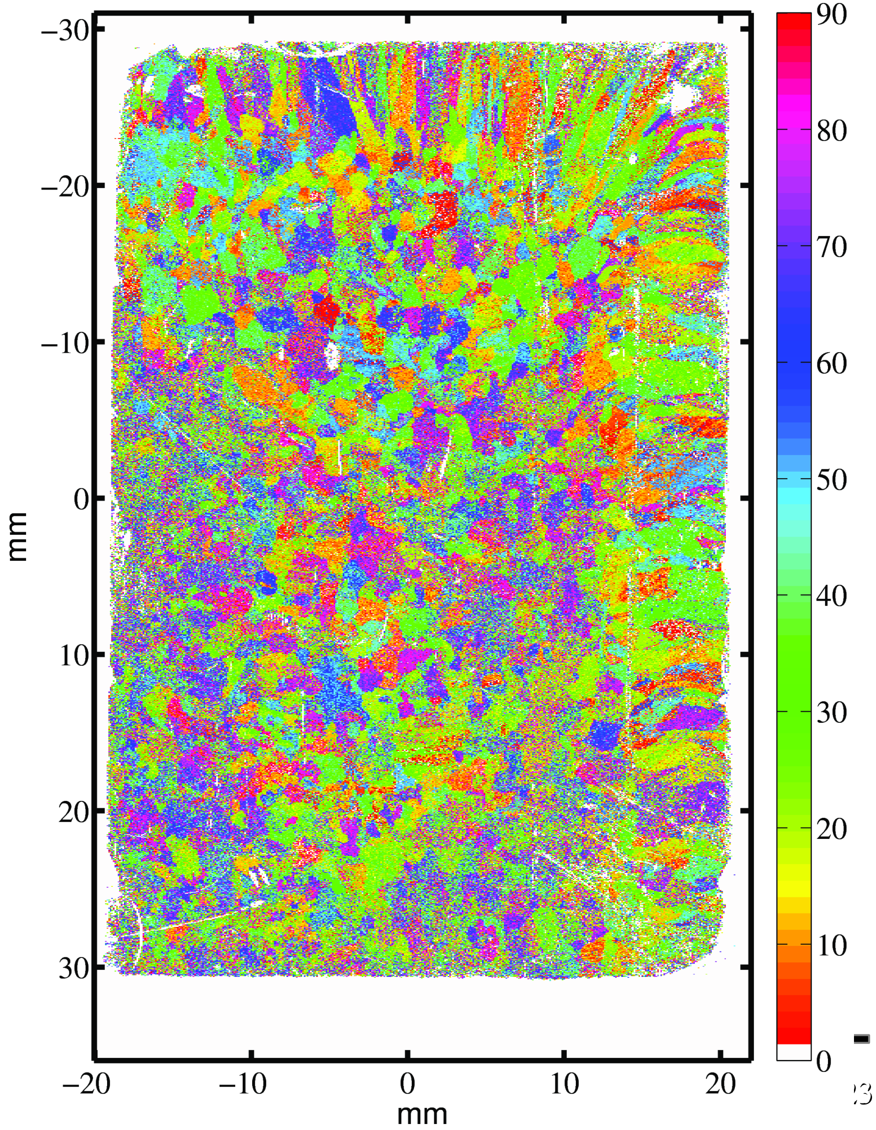
- Produces "EBSD-like" images
  - Lower spatial resolution (~50µm)
  - Over a much larger area (hundreds of mm)

Inconel



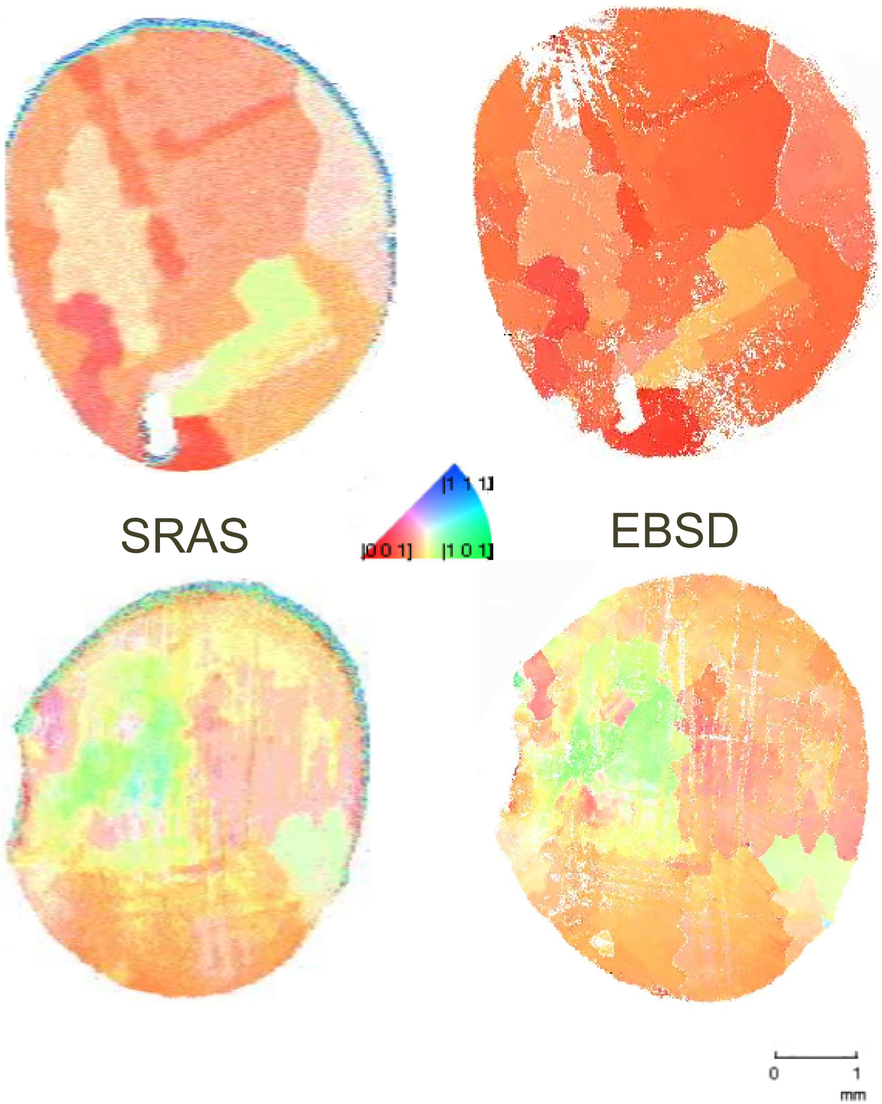
Large grain aluminium





SRAS (left) versus EBSD (right): Nickel superalloy

- SRAS scan time ~15-20 min per scan direction
- Pixel size 50x7μm (top), 25x7μm (bottom)
- Resolution: ~100μm
- EBSD images courtesy of John Aveson, Cambridge University



Part 6: Future work

- **Ability to deal with non-ideal surfaces***:*
  - *SKED (will be presented in half an hour)*
- **Scan on samples with complex geometry**
- **Monitoring technique for Additive Manufacturing**
- **Hexagonal crystals:** get the first two Euler angles
- **Separation of Ti alpha and Ti beta phases**
- **Elastic constants determination from multigrain materials SAW velocities**

Conclusion

SRAS is an innovative technique for orientation determination

- **Robust:** works on wide range of engineering materials: Ni, Al, Ti …
- **Non-contact and non-destructive**
- **Fast acquisition speed:** >1000 measurements per second
- **Simple sample surface preparation**: mirror-like finish (rough surface is feasible)
- **Capable of scanning large samples**: size only restricted by scanning stages
- **Can measure materials which have a thin coating/layer**

Thank you very much for your time!