Intensity contrast and distribution on the solar surface:
old wisdom with a surprising twist.

Oskar Steiner\textsuperscript{1,2}, René Salhab\textsuperscript{1} & Morten Franz\textsuperscript{1}

\textsuperscript{1}Kiepenheuer-Institut für Sonnenphysik (KIS), Freiburg i.Br., Germany
\textsuperscript{2}Istituto Ricerche Solari Locarno (IRSOL), Locarno Monti, Switzerland
1. Intensity rms contrast as a function of spatial resolution

**rms granular contrast** in continuum intensity vs. Fried parameter, $r_0$, of the SST. The **rms contrast increases with increasing** $r_0$ (better seeing).

From a slide of Göran Scharmer (Hinode 9 meeting, 2015, Belfast).
1. Intensity rms contrast as a function of spatial resolution (cont.)

We define here the *rms continuum intensity contrast* at a given wavelength $\lambda$ as

$$c_{\text{rms}} = \sqrt{\left\langle \left( \frac{I_{c,\lambda} - \langle I_{c,\lambda} \rangle}{\langle I_{c,\lambda} \rangle} \right)^2 \right\rangle}$$

rms granular contrasts from *spaceborne instruments* (quiet Sun, disk center)

<table>
<thead>
<tr>
<th>satellite</th>
<th>instrument</th>
<th>aperture</th>
<th>wavelength</th>
<th>$c_{\text{rms}}$</th>
<th>deconvolved</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDO</td>
<td>HMI</td>
<td>14 cm</td>
<td>617.3 nm</td>
<td>4.0 %</td>
<td>12.2 %</td>
<td>Yeo et al. (2014)</td>
</tr>
<tr>
<td>Hinode</td>
<td>SOT/BFI</td>
<td>50 cm</td>
<td>555.0 nm</td>
<td>8.0 %</td>
<td></td>
<td>Afram et al. (2011)</td>
</tr>
<tr>
<td>Hinode</td>
<td>SOT/SP</td>
<td>50 cm</td>
<td>630.0 nm</td>
<td>7.0 %</td>
<td>14.4 %</td>
<td>Danilovic et al. (2008)</td>
</tr>
</tbody>
</table>

**Old wisdom:** With *increasing spatial resolution* (telescope aperture), the *granular contrast increases.*
What about the simulations?

CO\textsuperscript{5}BOLD simulation with a grid-cell size of 10 km.

No magnetic fields.

Field of view 9.6 x 9.6 Mm

<table>
<thead>
<tr>
<th>( \lambda ) [nm]</th>
<th>500</th>
<th>630</th>
<th>bolometric</th>
</tr>
</thead>
<tbody>
<tr>
<td>rms</td>
<td>19.5%</td>
<td>13.7%</td>
<td>15.7%</td>
</tr>
</tbody>
</table>

Computation: Centro Svizzero di Calcolo Scientifico

Courtesy, \textit{F. Calvo, IRSOL}
1. Intensity rms contrast as a function of spatial resolution (cont.)

CO⁵BOLD simulation with a grid-cell size of 40 km (and more diffusive solver).
No magnetic fields.
Field of view 9.6 x 9.6 Mm

<table>
<thead>
<tr>
<th>λ [nm]</th>
<th>500</th>
<th>630</th>
<th>bolometric</th>
</tr>
</thead>
<tbody>
<tr>
<td>rms</td>
<td>19.1 %</td>
<td>13.6 %</td>
<td>15.9 %</td>
</tr>
</tbody>
</table>

λ = 500 nm
1. Intensity rms contrast as a function of spatial resolution (cont.)

CO$^5$BOLD simulation with a grid-cell size of 80 km

No magnetic fields.
Field of view 38.4 x 38.4 Mm

<table>
<thead>
<tr>
<th>$\lambda$ [nm]</th>
<th>500</th>
<th>630</th>
<th>bolometric</th>
</tr>
</thead>
<tbody>
<tr>
<td>rms</td>
<td>18.7%</td>
<td>12.9%</td>
<td>15.6%</td>
</tr>
</tbody>
</table>

bolometric intensity

Courtesy, G. Vigeesh, KIS
1. Intensity rms contrast as a function of spatial resolution (cont.)

rms granular contrast in % from simulations (quiet Sun, disk center)

<table>
<thead>
<tr>
<th>code</th>
<th>wavelength λ [nm]</th>
<th>cell size [km]</th>
<th>500</th>
<th>600</th>
<th>630</th>
<th>bolometric</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsuperscript{5} BOLD/Roe</td>
<td></td>
<td>10</td>
<td>19.5</td>
<td></td>
<td>13.7</td>
<td>15.7</td>
<td></td>
</tr>
<tr>
<td>CO\textsuperscript{5} BOLD/HLL</td>
<td></td>
<td>10</td>
<td>19.0</td>
<td></td>
<td>13.4</td>
<td>15.4</td>
<td></td>
</tr>
<tr>
<td>CO\textsuperscript{5} BOLD/HLL</td>
<td></td>
<td>12</td>
<td>18.8</td>
<td></td>
<td>13.3</td>
<td>15.4</td>
<td></td>
</tr>
<tr>
<td>CO\textsuperscript{5} BOLD/HLL</td>
<td></td>
<td>40</td>
<td>19.1</td>
<td></td>
<td>13.6</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td>CO\textsuperscript{5} BOLD/HLL</td>
<td></td>
<td>80</td>
<td>18.7</td>
<td></td>
<td>12.9</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td>MURaM</td>
<td></td>
<td>7.5</td>
<td></td>
<td></td>
<td>14.4</td>
<td></td>
<td>Danilovic et al. (2008)</td>
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<tr>
<td>CO\textsuperscript{5} BOLD</td>
<td></td>
<td>40</td>
<td>21.8</td>
<td></td>
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<td>14.4</td>
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<td>15.4</td>
<td>Beeck et al. (2012)</td>
</tr>
<tr>
<td>Stagger</td>
<td></td>
<td>40</td>
<td>22.1</td>
<td></td>
<td></td>
<td>15.1</td>
<td>Beeck et al. (2012)</td>
</tr>
</tbody>
</table>
1. Intensity rms contrast as a function of spatial resolution (cont.)

**Surprising twist:** The granular *rms contrast of simulations* stays fairly constant as a function of spatial resolution.

**Corollary:** A simulation of low spatial resolution is not equivalent to a low resolution observation.

**Physical reason:** Limited convective velocities and given energy flux \( T_{\text{eff}} \) fixes the intensity contrast.
1. Intensity rms contrast as a function of spatial resolution (cont.)

Åke Nordlund during the discussion at a Sac Peak Workshop (approximate quote to my recollection):

“I have this high contrast from the very beginning. In the course of time I have seen observers to report higher and higher values and I am confident that in near future they will converge to my value.”

For the production of synthetic intensity maps one best starts from a simulation of highest possible spatial resolution and subsequently applies the modulation transfer function of the observational instruments.

See, e.g., Danilovic et al. (2008, A&A 484, L17)
2. Intensity distribution as a function of spatial resolution

Disk-center radiative intensity distributions from observations.

Hinode/SP (black) 630 nm vs. Sunrise/IMaX (grey) 525 nm

Hinode/SP vs. Sunrise/IMaX reconstructed
2. Intensity distribution as a function of spatial resolution (cont.)

Distribution of the relative intensity of the vertically propagating radiation at $\lambda = 500$ nm, 630 nm, and bolometric of a CO$^5$BOLD simulation of moderate spatial spatial resolution. The grid-cell size is 40 km. The distribution is bimodal.

This bimodal distribution is also seen in simulations of stellar atmospheres others than the Sun. Trampedach et al. (2013, ApJ 769, 18) fit it with the double Gaussian

$$n(I) = I_1 e^{((I-I_2)/I_3)^2} + I_4 e^{((I-I_5)/I_6)^2}$$

Tremblay et al. (2013, A&A 557) show distributions over a wide range of stellar types.
2. Intensity distribution as a function of spatial resolution (cont.)

10 km

area fraction in %

12 km

area fraction in %

40 km

area fraction in %

80 km

area fraction in %
2. Intensity distribution as a function of spatial resolution (cont.)

$\lambda = 500$ nm

Cell size 10 km, high-res solver

Cell size 40 km, low-res solver

common gray scale: $0.65 \leq \frac{I}{\langle I \rangle} \leq 1.35$
2. Intensity distribution as a function of spatial resolution (cont.)

**Surprising twist:** The bimodality of the intensity distribution becomes less prominent with increasing spatial resolution.

Different from the rms contrast, the intensity distribution *does* depend on the spatial resolution of the simulation.
3. Non-magnetic bright points

Bolometric intensity maps


With magnetic fields: Magnetohydrodynamic simulation.
Without magnetic fields: Hydrodynamic simulation
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3. Non-magnetic bright points

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