Long range imaging with optical sensors

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What is long range?

- To read the text on a coin at 50 m
- To recognize a face at 200 m
- To recognize a handheld object at 2-3 km
- To detect and ID a vehicle at 10+ km
- To see hidden objects (prolonged ranges)
- In astronomy: many many light years
How can we see clear at long range?

- Big optics
- Large FPA with many small pixels
- Beat other physics limitations
  - Diffraction limit
  - Mechanical blur
  - Atmosphere
    - Scattering and absorption
    - Turbulence
    - ........
Really long range imaging (VLTI in Chile)

Laser guide star for turbulence compensation

The central 5,500 light-years wide region of the spiral galaxy NGC 1097

Resolution (interferometric mode): ±0.08 milli-arc-seconds = 3.8*10^{-10} rad or about 17 cm at the moon surface (car recognition)
Problem: How to combine wide FOV with ID at long range (small FOV)

ARGUS-IS (Autonomous Real-Time Ground Ubiquitous Surveillance Imaging System),

- 1.8 gigapixel image (several hundred smart phone sensors)
- 6 000 m altitude
- ARGUS can keep a real-time video eye on an area 41 km²
- Resolution on the ground 15 cm

Source Internet
Development of IR FPA detectors

10,000 * 10,000 = 100 Megapixels
Resolution limitations

- Resolution limitations
  - **Diffraction** $\lambda/D$
  - $d_{\text{pix}}/F$
  - Atmosphere
    - Turbulence
    - Aerosol scatter
  - Plattform jitter movement
  - Optics aberation (coma, astigmatism....)
    - Many optical elements
    - Curved focal planes

$$\theta_{\text{min}} = \max(d_{\text{pix}}/F, \lambda/D)$$

Ex Diffraction limit $\lambda/D$
- $\lambda=0.5$ $\mu$m, $D=5$ cm; $\theta_{\text{min}}=10$ $\mu$rad
- and $\lambda=10$ $\mu$m, $D=5$ cm; $\theta_{\text{min}}=200$ $\mu$rad
Corresponding to 1 cm (20 cm) at 1 km range
Resolution limitations 2(X)

- Atmospheric turbulence

Fried’s parameter

\[ r_0 = \left[ 0.423 k^2 \int_0^L C_N^2(z) \left( \frac{z}{L} \right)^{5/3} \, dz \right]^{3/5} \]

Angle resolution due to turbulence \( \theta = \frac{\lambda}{r_0} \)

As compared to \( \max (\frac{\lambda}{D}, \frac{d_{\text{pix}}}{F}) \)
Slant path active/passive imaging at 2 km-1.5 µm

Ground turbulence 2E-13 m^{-2/3}

Active

Passive

H=1.6 m                             5.15                                       7.65                                   13.15

Active and passive short-wave infrared and near-infrared imaging for horizontal and slant paths close to ground

Ove Steinvall, Magnus Elmqvist, Tomas Chevalier, and Ove Gustafsson
10 July 2013 / Vol. 52, No. 20 / APPLIED OPTICS
Ex active imaging at long ranges (well above ground-low turbulence)
The effects of weak turbulence conditions can be compensated by processing on a global scale. Such processing can be done in real-time.
Plattform motion/vibration gives image blur

Left input from a UAV sensor. Right processed imaging using motion compensation, super-resolution and contrast enhancement.
Ex. Turbulence mitigation  active imaging

Single shot  Frame average + deconvolution
Can be implemented in real time

Advanced short-wavelength infrared range-gated imaging for ground applications in monostatic and bistatic configurations
Repasi, Endre; Lutzmann, Peter; Steinvall, Ove; Elmqvist, Magnus; Göhler, Benjamin; Anstett, Gregor
DRI of a human target with respect to turbulence strength

<table>
<thead>
<tr>
<th>Turbulence Strength</th>
<th>Detection [km]</th>
<th>Recognition [km]</th>
<th>Identification [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>weak</td>
<td>22.7</td>
<td>10.0</td>
<td>5.4</td>
</tr>
<tr>
<td>moderate</td>
<td>16.0</td>
<td>8.1</td>
<td>4.7</td>
</tr>
<tr>
<td>strong</td>
<td>8.6</td>
<td>4.3</td>
<td>2.8</td>
</tr>
<tr>
<td>very strong</td>
<td>3.2</td>
<td>1.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Source Karen Stein IOSB/ Fraunhofer
Ex. Aerosol scatter and absorption, 1.8 km path over water

Visible (passive)
kl. 9.09 (V=50 km)  kl. 15.04 (V=7 km)  kl. 17.04 (V=50 km)  kl. 19.29 (V=6 km)

LWIR (QWIP)

LWIR, TV
Active gated NIR
Illuminated non gated SWIR

Passive and active EO sensing close to the sea surface
Ove Steinvall, Rolf Persson, Folke Berglund, Johan Öhgren, Frank Gustafsson
SPIE 8250-8, 2014
New concepts for long range imaging

• Superresolution
• Lucky Imaging
• High res 1 D imaging - tomography
• SAL
• Multiaperture
• Coded aperture
• Adaptive optics
• Single photon counting/fast time gating
  • See through clouds
  • See round the corner
Superresolution (improving res. beyond $\lambda/D$)

- **Multiplexing spatial-frequency bands**, e.g., structured illumination
- **Multiple parameter use within traditional diffraction limit**, e.g. polarization, different wavelengths
- **Multiple-frame SR uses the sub-pixel shifts** between multiple low resolution images of the same scene. It creates an improved resolution image fusing information from all low resolution images, and the created higher resolution images.

Source: IEEE TRANSACTIONS ON IMAGE PROCESSING, VOL. 13, NO. 10, OCTOBER 2004 1327
Fast and Robust Multiframe Super Resolution
Sina Farsiu, M. Dirk Robinson, Student Member, IEEE, Michael Elad, and Peyman Milanfar, Senior Member, IEEE
Lucky Imaging

Anisoplanatic Imaging: Lucky Region Fusion Technique

- Turbulence induces variations ("mutations") in local image quality including random appearance of high-resolution image regions ("lucky regions"). Conventional imaging systems throw away these "lucky" regions.

- Micro-lensing phenomenon caused by turbulence enables the capture of additional information, that is lost in conventional imaging systems due to averaging.

- Turbulence creates "mutations" in local image quality.

- Imaging through exploitation of a random media focusing effect by "lucky" regions fusion.

Source DARPA
Probability of lucky image horiz. path 1 km

\[ \text{Prob} \approx 5.6 \exp\left[-0.1557 \left(\frac{D}{r_0}\right)^2\right] \]

Tomography

High resolution is preserved long ranges
Target need not be angular resolved

Simulations by T Chevalier  FOI (now Saab)
Tomography

Log intensity waveforms

Tomographic reconstruction

Range 0.6 mm per sample

Photon counting lidar work at FOI, Sweden

Ove Steinval*, Lars Sjöqvist and Markus Henriksson

Proc. of SPIE Vol. 8375 83750C-8 2013
Long range photon counting imaging and profiling

Range accuracy of better than 4cm

TCSPC for optics profiling

9 km range

Target discrimination strategies in optics detection

Proc. of SPIE Vol. 8898, 88980K · © 2013 SPIE
SAL Mission: ID at Range
“Resolution of a SAR with interpretability of an EO Sensor”

Goal: Bring ID Capability to Detection Ranges
Provide High Resolution Imaging Beyond the Diffraction Limit

RF/EO WIDE AREA SEARCH
Localize, Prioritize, Cue

REACQUISITION & PROSECUTION

ONE STEP WITH ID AT RANGE

What if bomber crews or GLOBAL HAWK had ID capability at operational ranges?

Imaging a car in Linköping from Stockholm?

SAL CAN PROVIDE IT
- Resolution of a High Performance SAR
- EO Like Images
- Fast Image Times on queued Targets
- Must be cued small field of view

Source: Phil Tomlinson et.al. CLR 2007
Many laboratory demonstrations
  - USA, China, Canada, ……

Relatively few (open) demos at long ranges
  - DARPA SALTI program (classified)-airborne
  - Airborne demo CTI, US (Open)
  - MIT (Firepond…)

Ex onging program
  - DARPAS Long View ISAL of geo-stationary satellites (36 000 km)
Firepond ladar MIT

Imaging of space objects
Imaging a 60 cm satellite at 5900 km
Firepond ladar MIT
Cf. SAL and SAR

<table>
<thead>
<tr>
<th>Feature</th>
<th>SAL</th>
<th>SAR</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>High angular resolution</td>
<td>+</td>
<td>0</td>
<td>Resolution $\lambda/D$ or $\lambda/VT$</td>
</tr>
<tr>
<td>Exposure time</td>
<td>++</td>
<td>0</td>
<td>$T_{\text{exp}}$-lidar $10,000$ shorter than SAR</td>
</tr>
<tr>
<td>FOV</td>
<td>0</td>
<td>++</td>
<td>Beam width $\lambda/D$</td>
</tr>
<tr>
<td>Weather influence</td>
<td>0</td>
<td>++</td>
<td>This is a great disadvantage for SAL. Both aerosols and turbulence</td>
</tr>
<tr>
<td>Look into urban canyons</td>
<td>++</td>
<td>0</td>
<td>SAR has interference problems</td>
</tr>
<tr>
<td>Covertness</td>
<td>++</td>
<td>0</td>
<td>No sidelobes for SAL</td>
</tr>
<tr>
<td>3-D imaging</td>
<td>++</td>
<td>0</td>
<td>Very high for SAL. Radar limited by interference between scatterers</td>
</tr>
<tr>
<td>Frequency allocation</td>
<td>++</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Technical maturity</td>
<td>0</td>
<td>++</td>
<td>Airborne SAL first demonstrated 2006.</td>
</tr>
</tbody>
</table>
Multiaperuture: real time processing scheme using phase information

Outdoor experiments

Lensless **Coded Aperture Imaging**

- Conventional lens technology is constrained by the lack of materials which can effectively focus the radiation within reasonable weight and volume
- *Programable* software-defined optics have revived interest in coded apertures
- Extends the pinhole camera concepttutes

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Source, Michael J DeWeert* and Brian P. Farm
BAE Systems Spectral Solutions, SPIE Baltimore 2014
Jfr kodad apertur med konventionell lins

(b) O2 Mask
Four Orientations
summed

(c) Truth Image
from conventional camera

Source, Michael J DeWeert* and Brian P. Farm
BAE Systems Spectral Solutions, SPIE Baltimore 2014
See through-prolonging your line of sight using active imaging
3 D ladar for looking through camouflage

Images D Letalick, H.Larsson FOI
Foreground filtering using 3D ladar

Spatial filtering for detection of partly occluded targets
C. Grönwall, G. Tolt, T. Chevalier, H. Larsson
Window/door reflection (independent on surrounding light/darkness)
Also for diffuse targets......

How it works...

MIT camera culture group

Conclusions

• Established methods for long range viewing
  • Large apertures
  • New large high resolution FPAs
  • Turbulence mitigation in real time (Note: only for weak to moderate turb.)
  • Long range active gated imaging to beat aerosol scatter

• A number of new concepts
  • Superresolution, Lucky Imaging, Fast cameras + processing
  • High res 1 D imaging-tomography, Fast laser range finder + processing
  • Synthetic aperture lidar (SAL, + ISAL), Coherent techniques
  • Multiaperture
  • Coded aperture Relax demands on one big telescope
  • Adaptive optics
  • See through clouds using active systems
  • See round the corner using active systems
  • Time resolved photon counting
• Thank you!