Introduction to Astronomical Image Processing

3. Image processing goals

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Image processing goals

- The 4 processing levels
  - Radiometric **calibration** *(very low level)*
  - Observational effects **correction** *(low level)*
  - Data **preparation** *(mid level)*
  - Astronomical data **analysis** *(high level)*

- Image processing workflows
  - Principle
  - Drawbacks

- Error modeling and propagation
  - Understanding the error sources
  - Simple propagation vs. entanglement
  - Result uncertainties and statistical significance
The 4 different processing levels

- Understand the difference between calibration, correction, preparation and analysis
- Sort the methods according to the image formation hierarchy (invert the observation process)
- Sort the processing tools by computational complexity
1. Radiometric calibration *(very low level)*
   Sensor Pixel & Instrument point response compensation:
   dark current, non-linearity, pixel-dep. sensitivity, bad pixels
   Sky effects removal (spatial & spectral effects):
   atmospheric absorption/extinction, sky and interplanetary background

2. Observational effects correction *(low level)*
   Blur (diffraction, aberrations, diffusion, motion), noise, geometric distortions, data scrambling, image multiplicity & redundancy

3. Data preparation *(mid level)*
   Visualization of complex datasets
   Dimensionality issues, complex redundancy cases
   Information content hidden in noisy observations

4. Astronomical data analysis *(high level)*
   Imaging known astronomical objects (parametric or not)
   Observing unknown or poorly defined objects
Radiometric calibration (very low level)

Processing tools:

- Single pixel operations
  - Additive bias: *subtraction*
  - Multiplicative effects: *division*
  - Non-invertible transform: *labeling*

- Multiple pixel operations
  - Non-invertible transform: *rank filtering, interpolation*

- Prerequisites:
  - Sensor / optics / sky calibration:
    - evaluate the degradations
    - *basic operations, rank filtering, etc.*
Observational effects correction (low level)

Processing tools:

- Multiple pixel operations, one step
  - Blur: *filtering (transform, kernel)*
  - Noise: *filtering (transform, kernel, order)*
  - Redundancy: *averaging & interpolation (resampling)*
  - Distortion, scaling, rotation, shift: *interpolation (resampling)*
  - Scrambling: *interpolation (resampling)*

- Multiple pixel operations, complex, iterative
  - Blur: *inverse iterative methods (deterministic, stochastic)*
  - Noise: *inverse iterative methods (deterministic, stochastic)*
  - ...
Data preparation (mid level)

Processing goals & tools:

- **Image enhancement & presentation**
  - Poor visual detection: *enhancement (radiometric transform, spatial filtering), multiresolution support*
  - Too many bands: *3-color visualization (linear algebra, averaging, transforms)*

- **Dimensionality & redundancy reduction**
  - Curse of dimensionality: *reduction (linear algebra, averaging, ...)*
  - Redundancy: *data fusion (iterative/recursive reconstruction)*

- **Information discovery**
  - Low SNR: *adaptive binning*
  - Unknown sources: *iterative reconstruction (nonlinear fitting, model selection, transforms)*
Astronomical data analysis (high level)

Find, measure known objects

- **Object parameter estimation**
  - Find parametrized objects: correlation, maximum finding
  - Find shape-characterized objects: math. morphology
  - Measure characteristics (location, size, etc.): moments

- **Object analysis & classification**
  - Parameter classification: discrete/fuzzy decision rules
  - Pixel or parameter interpretation (physically meaningful): basic ops, or apply equations...

Unsupervised known object analysis

Unsupervised classification: data-driven decision rules

Find unknown objects

- Eliminate known objects vs. blind object separation
- Find objects: priors not fixed anymore!
- Tests: decision rules
Image processing workflows and error propagation

- Become familiar with image processing chains or workflows
- Be aware of the limitations of the workflow (sequential) approach
- Remember that the results should always come with error bars
- Understand how errors should propagate through a workflow
Image processing workflows (chains, pipelines)

Block-diagrams:
Node = processing algorithm
input → processing → output
Arrow = data flow

e.g. Khoros/Cantata, Visiquest (Accusoft)

Nicmos processing pipeline (HST)
A typical image processing workflow

Example: noisy/blurred/scaled image classification

Sequential processing (workflow)

Equivalent global algorithm?
Drawbacks of image processing chains

- Lack of global understanding
  - The block decomposition is not unique
  - Some algorithms may not be decomposed into simple atoms
    e.g. compound geometric transforms

- Accuracy is sufficient only in the simplest cases
  - Sequential methods = approximations of global algorithms
  - Error propagation, difficult to control
  - Usually uncertainties are not taken into account
    - Processing an image changes the noise statistics
    - The block approach implicitly makes strong assumptions on the input noise: wrong after processing!
Error modeling: from source to result

- Input noise: stochastic process
  - Observation = realization of a random variable
  - Several additive processes, zero mean
  - Stochastic independence between pixels (white noise)
  - Stationary process (although parameters may be non-stationary)

- Processing algorithm: deterministic transform

- Output noise: stochastic process
  - Result = realization of a random variable
  - Additive & zero mean assumption, stochastic independence, stationary
Simple error propagation vs. correlation

- **Simple error propagation model**
  - Gaussian assumption: $X \sim N(\mu, \sigma^2)$
  - Independence assumption (true for single pixel operations)
  - Add a variance map to the image (variance for each pixel)
  - **Rules:** Linear transform $aX + b \sim N(a\mu + b, (a\sigma)^2)$
    Nonlinear transform: Laplace approx
    \[
    f(u) \approx f(\mu) + (u - \mu) \frac{\partial f}{\partial u}|_{\mu}
    \]
    \[
    \sigma^2 \mapsto (\frac{\partial f}{\partial u}|_{\mu})^2 \sigma^2
    \]

- **Variable entanglement or correlation**
  - Multiple pixel operations $\Rightarrow$ stochastic dependence btw. pixels
  - e.g. bilinear interpolation
  \[
  f(x, y) \approx f(0, 0)(x-1)(y-1) - f(1, 0)x(y-1) - f(0, 1)(x-1)y + f(1, 1)xy.
  \]

- Use an inverse covariance matrix (sparse) and propagate it...
Result uncertainties & confidence regions

95% confidence interval
(Normal distribution)

- log posterior pdf
- log \( \text{P(param|obs)} \)

Contour plots show 2D confidence regions

Results should always come with error bars!
Image processing goals: conclusion

- Provide an estimate of the result (mean)
  - Classical image processing approach: provide an image
  - Classical parameter estimation: provide a point estimate

- Provide a rough estimate of the error
  - If possible, compute the error (variance) for each pixel (approximation: stochastic independence)
  - Provide error bars for each parameter (same assumption)

- Provide a more rigorous estimate of the uncertainty
  - If possible, build an inverse covariance matrix and use it! (each entry relates to single or interacting pixels)
  - Propagate this matrix and invert it only in the final step
  - Provide the covariance matrix for the parameters