Joint ICTP-IAEA Workshop on Monte Carlo Radiation Transport and Associated Data Needs for Medical Applications

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ICTP, Trieste, Italy

Lecture 29

egs++ applications: egs_kerma and egs_cbct

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`egs_kerma`: **Calculating Kerma in a volume**

Main goal: *Efficient* estimation of kerma in a scoring volume defined by one or more geometrical regions of the same material.

- Kerma in each scoring region and the whole volume.
- Total and differential photon fluence ONLY in the whole scoring volume.
- Since one could potentially want to calculate kerma for secondary photons, charged particles are transported. Turn it OFF by setting high enough `ECUT`

Scoring options

- Multiple calculation geometries can be defined.
- Geometrical regions spanning the scoring volume are provided via the `scoring regions` key.
- Kerma estimation in each region activated by providing as many entries for the mass as for the scoring regions.
- There is an option to exclude the contribution from photons passing through certain regions, which is useful for estimating the effect of those regions on the quantities scored (kerma and fluence).

Note: The reason one must specify the scoring masses is that a generic algorithm for computing arbitrary volumes has not been included to date in `egs++`.

Scoring options input block

```
:start scoring options:
   :start calculation geometry:
       geometry name          = name_1
       scoring regions        = list_of_regions
       scoring region masses = mass in g for each region
       #Exclude particles touching these regions
       excluded regions       = list_of_regions
   :stop calculation geometry:
   :start calculation geometry:
       geometry name          = name_2
       ...
   :stop calculation geometry:
   ...
   :start calculation geometry:
       geometry name  = name_n
       ...
   :stop calculation geometry:
:stop scoring options:
```

- If no valid scoring region is entered, the calculation geometry is ignored.
- If an error in the scoring region input is detected, code aborts with a warning message

Defining scoring regions

- Simply enter scoring regions individually

```
    :start calculation geometry:
        (...)
        scoring regions = ir1 ir2 ir3 ... irN
        (...)
    :stop calculation geometry:
```

- Pairs of initial and final scoring regions

```
    :start calculation geometry:
        (...)
        scoring region ranges = ir1 fr1 ir2 fr2 ir3 fr3 ... irN frN
        (...)
    :stop calculation geometry:
```

Defining scoring regions

- Groups of regions

```
:start calculation geometry:
    (...)
    scoring start region = ir1 ir2 ir3 ... irN
    scoring stop region  = fr1 fr2 fr3 ... frN
    (...)
:stop calculation geometry:
```

- Groups of equally spaced scoring regions

$\longrightarrow$ expects triplets of initial, final and increment regions

$\longrightarrow$ scoring at specified intervals (increments) between regions

```
:start calculation geometry:
    (...)
    incremental scoring regions = ir1 fr1 dr1 ... irN frN drN
    (...)
:stop calculation geometry:
```

Scoring regions mass input schemes

Using ‘scoring region masses‘ input key

```
:start calculation geometry:
    (...)
    scoring region masses = m1 ... mN # in g
    (...)
:stop calculation geometry:
```

a) One value per region, regardless of scoring region input scheme
b) One value per group (pair or triplet)
c) One value for all regions (positive)
d) One value for whole scoring volume (negative)

Using ‘scoring volume mass‘ input key assumes mass for whole scoring volume as in d).

```
:start calculation geometry:
    (...)
    scoring volume mass = m  # in g
    (...)
:stop calculation geometry:
```

Correlated scoring

- A correlated scoring of kerma ratios can be requested by linking any combination of two calculation geometries which might result in a more efficient estimator.
- In cases of small differences between these geometries, the ratios `will be strongly correlated`, resulting in a significant reduction of the variance.
- Correlated scoring is requested by assigning two geometry names to the `correlated geometries` key:

```
:start scoring options:
   ...
   correlated geometries = name_i name_j
    ...
:stop scoring options:
```

Forced detection

If reaching the scoring volume is very unlikely, efficiency significantly increased by using forced detection (FD).

- Combines an exponential track-length (eTL) estimator with a geometry-guided ray-tracing algorithm.
- Photons contribute to the scoring without having to reach the scoring volume.
- Define geometry encompassing all scoring regions to guide a ray-tracing algorithm, which computes the path to and across the scoring regions
- Efficient scoring using an exponential track-length estimator (eTL).

Dramatic efficiency increases can be obtained when there is significant attenuation, e.g., kV imaging, shielding calculations, etc.

Forced detection inputs

```
:start scoring options:
   :start calculation geometry:
       geometry name         = name_1
       ...
        FD geometry           = FD_geometry_name
   :stop calculation geometry:
   ...
   :start calculation geometry:
       geometry name  = name_n
       ...
   :stop calculation geometry:
   ### geometry for forced-detection
   #   Used for calculation geometries for which
   #   no FD geometry defined.
   Default FD geometry = sphere
:stop scoring options:
```

- FD geometries can be specified for individual calculation geometries in their corresponding definition input block.
- One can also define a generic FD geometry for those calculation geometries without one.
- If omitted, scoring ONLY when reaching scoring region

`egs_cbct`: **simulating CBCT scans**

- Simulates a cone-beam computed tomography (CBCT) setup by scoring the photon beam contribution (air kerma) to a planar detector after going through a phantom at arbitrary angles on a circular orbit around one of the coordinate axes (x-axis, y-axis or z-axis).

- **Main goal:** very fast estimation of scatter contribution to detector to be used in a correction algorithm based solely on Monte Carlo calculations.

- Estimates total signal to detector and its transmitted and scattered components.

- Makes use of several VRTs and a smoothing algorithm increasing scatter estimation efficiency by several orders of magnitude.

Details of the correction algorithm and the VRTs used can be found in

- **Phys. Med. Biol. 55,** 16, 4495–4507 (2010)
- **J. Phys.: Conf. Ser. 102,** 012017 (2008)

CBCT scans

Kilovoltage CBCT scans are generated by rotating an x-ray tube and a 2D detector together in a circle around the body, recording 2D projection images at different angles.

The basic measurement of a CT scanner is a line integral of the linear attenuation coefficient μ at the effective energy of the scanner $\bar{E}$:

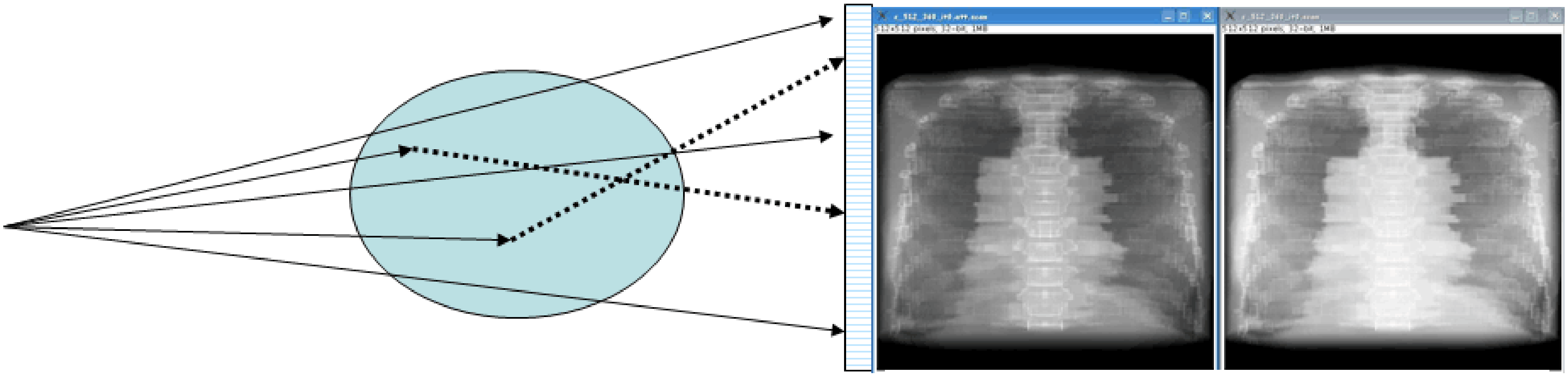
$$s_i = -\ln \frac{R_i - S_i}{b_i} = -\ln \frac{A_i}{b_i} = \int \mu\left(l, \bar{E}\right) dl$$

where R_i is the **real scan** signal measured by the scanner in pixel i for a given projection, b_i is a **blank scan** (a scan without the phantom), S_i is the corresponding **scatter contribution** to the real scan, and A_i is the **attenuated** signal (scatter-free).

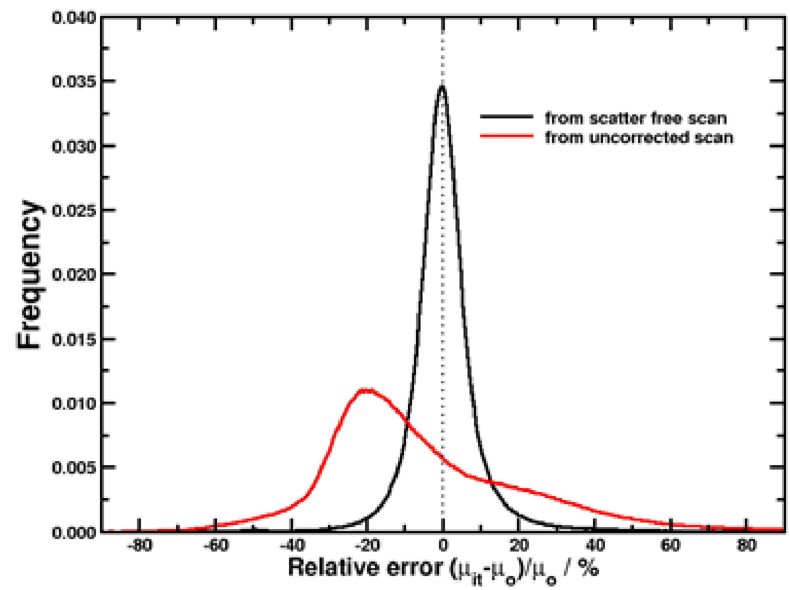
Ideally S_i is small enough that it can be neglected in which case $R_i \approx A_i$.

However, in CBCT, S_i can be very large and there is a need to know S_i for accurate image reconstruction.

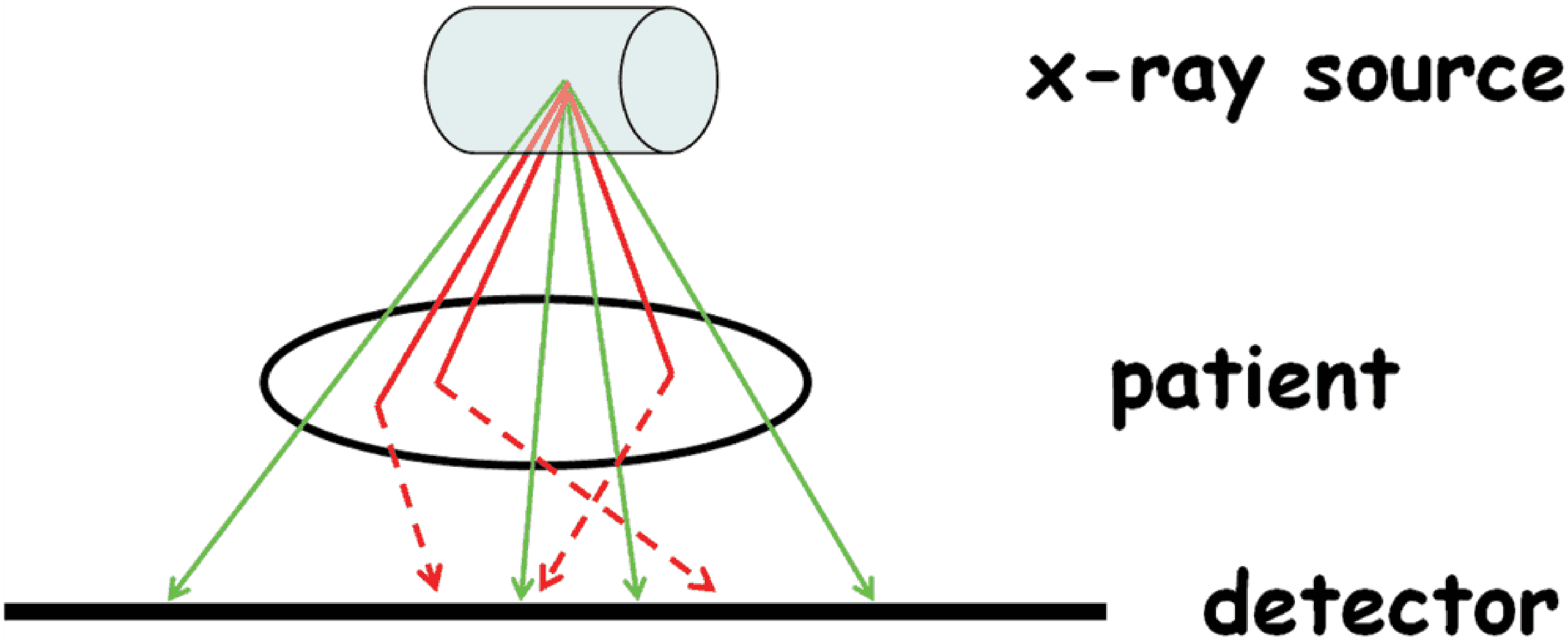
CBCT scatter problem



- Reduces image contrast resolution
- Increases image noise
- Streak and cupping artifacts
- Increases patient dose



egs_cbct: **Goal**



Goal: FAST estimate of scatter correction by means of MC ONLY.

Geometry definition: blank scan

```
:start geometry definition:

    ##################################### blank phantom
    :start geometry:
       library = egs_ndgeometry
       type    = EGS_XYZGeometry
       x-slabs = -15 30 1
       y-slabs = -15 30 1
       z-slabs = -15 30 1
       name    = blank_phantom
       :start media input:
            media = VACUUM, AIRICRU512
       :stop media input:
    :stop geometry:

    simulation geometry = blank_phantom

:stop geometry definition:
```

Geometry definition: voxelized human phantom

The voxelized human phantom (VHP) geometry was developed for using the **Female Adult voXel phantom**(FAX06) which was kindly contributed by R. Kramer.

```
###################
#        fax06
###################
:start geometry:
    library             = egs_vhp_geometry
    name                = fax06
    slice range         = 0 180
    phantom data        = $EGS_HOME/egs_cbct/fax06_med1.bin
    media data          = $EGS_HOME/egs_cbct/head.data
:stop geometry:
```

R Kramer et al., **Phys. Med. Biol. 51,** 3331–3346 (2006)

Geometry definition: XYZ Geometry representation

To change the VHP phantom resolution and its position one can voxelize the VHP geometry into an XYZ geometry and apply an affine transformation:

```
:start geometry:
    library = egs_ndgeometry
    type    = EGS_XYZGeometry
    name    = voxelized_fax06
    x-slabs = -25.68 0.200625 256
    y-slabs = -25.68 0.200625 256
    z-slabs = -25.68 0.200625 256
    # geometry to be voxelized
    voxelize geometry = fax06
    # The transformation to be applied before
    # looking up the medium in the fax06 geometry
    :start transformation:
        translation = 28.44 13.2 10.8
    :stop transformation:
    delete geometry = no
:stop geometry:
```

Particle source definition

- Any source from the egspp source module can be used.
- By default sources are placed at the origin and directed along the positive z-axis. To position the source elsewhere, apply an affine transformation.

Scoring options input block

This input block defines the calculation geometry and detector details.

```
:start scoring options:

    calculation type = planar # or ray-tracing

    :start calculation geometry:
        geometry name = phantom
    :stop calculation geometry:

    :start planar scoring:

    # (see next slide ...)

    :stop planar scoring:

:stop scoring options:
```

Calculation types

- planar: Scores kerma at an user-defined plane, by default at origin along z-axis
- ray-tracing: As above, but only traces primary photons across geometry
- volumetric: Scores kerma in a volume. Not available yet!

Using `ray-tracing`, ideal and blank scans can be obtained in about 4X less time.

Scoring options: planar scoring

- defines detector details
- Fraction S/S$_{\rm max}$ above which to compute scatter efficiency
- E$\cdot\,(\mu_{en}/\rho)_{\rm air}$ values file name.

```
:start planar scoring:
    minimum Kscat fraction = 0.5 # eff for S/Smax > 0.5
    surrounding medium = VACUUM #AIRICRU512
    # Detector details
    screen resolution = 64 64
    voxel size = 1.25
    :start transformation:
         rotation    = 0 -1.5707963267948966 19 0
         translation = 55 0 0
    :stop transformation:
    # Uses file provided in the distribution
    muen file = full_path_name
:stop planar scoring:
```

Output options

Producing all scans

```
:start output options:
    display type       = total    # total, attenuated, scattered
    store signal map   = no       # yes, no (default)
    store data arrays = yes      # yes (default), no
    :start scan output:
        # all, real, scatter, ideal, blank, none
        scan type   = all
        scan file   = absolute_real_scan_file_name
        blank scan = absolute_blank_scan_file_name
    :stop scan output:
:stop output options:
```

Producing a blank scan

```
:start output options:
    display type       = total    # total, attenuated, scattered
    store signal map   = no       # yes, no (default)
    store data arrays = yes      # yes (default), no
    :start scan output:
        scan type = blank
        scan file = absolute_blank_scan_file_name
    :stop scan output:
:stop output options:
```

CBCT setup

- Initial position set once `source` and `scoring plane` defined.
- CBCT system can be rotated using this input block
- Needed even if no rotation desired (0$^{\mathrm{th}}$ projection)

```
    :start cbct setup:
        minimum angle =   0 # Default: 0 degrees
        maximum angle = 360 # Default: 0 degrees
        step          = 45  # angular intervals in degrees
        projection    = 1   # from 0 to (max - min)/step
        rotation axis = z   # x, y, or z (default)
    :stop cbct setup:
```

CBCT setup

- Initial position set once `source` and `scoring plane` defined.
- CBCT system can be rotated using this input block
- Needed even if no rotation desired (0^{th} projection)

```
:start cbct setup:
    orbit       = 360 # full angular range
    step        = -45 # interval width in degrees
    #x-rotation = 0   # rotation around x axis
    #y-rotation = 0   # rotation around y axis
    z-rotation  = 0   # rotation around z axis
:stop cbct setup:
```

Variance reduction techniques (VRTs)

- **Forced detection** (FD)
- **Woodcock tracking** (delta transport)
- **Mean free path transform** (MFPTR)
- **Splitting** and **Russian Roulette** (splitting+RR)

- Use for estimation of the scatter contribution.
- Not needed for blank scan calculations.
- For real scans one should avoid using VRTs since these techniques are aimed at enhancing scatter but could cause undersampling of the primary contribution for instance.
- However, fixed splitting combined with Russian Roulette gives some gain even when computing a real scan (*measured*).

For more information: **Phys. Med. Biol. 55,** (16), 4495–4507 (2010)

Smoothing scatter distribution

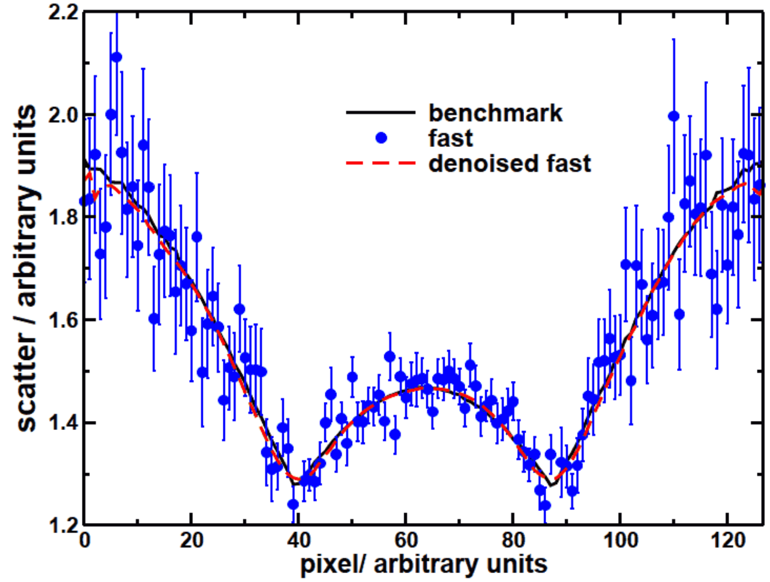
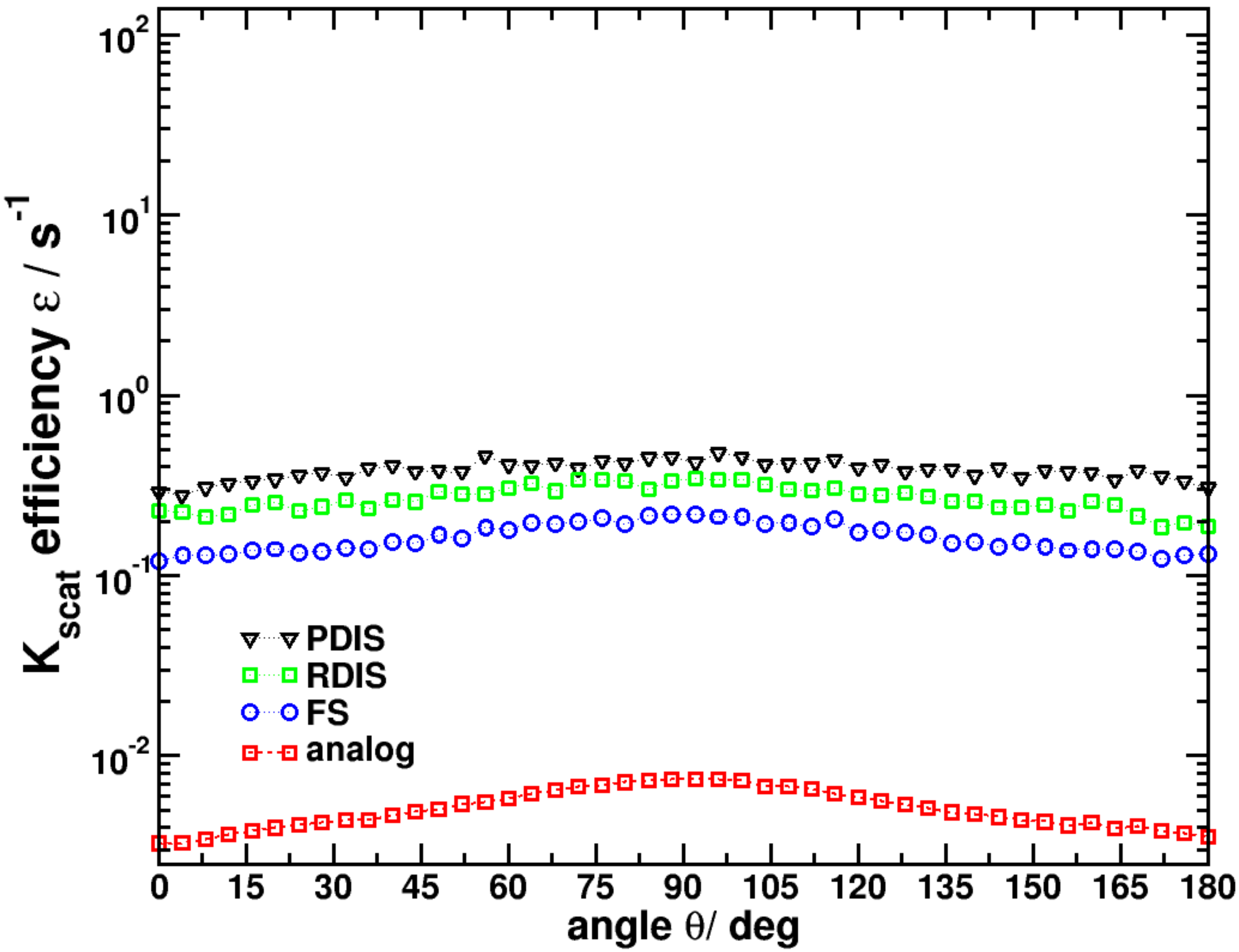


Figure 6.4: Comparison of the scatter distributions from calculations with a negligible uncertainty (black line), a large statistical uncertainty obtained in 15 seconds of CPU time (red symbols) and the fast calculation after denoising (blue line) for a simple homogeneous water cylinder irradiated with a 60 keV photon beam.

Adapted the 3D locally-adaptive Savitzky-Goley filter used in VMC++ to 2D see *On the de-noising of Monte Carlo calculated dose distributions by I Kawrakow* **(2002 Phys. Med. Biol. 47 3087)**

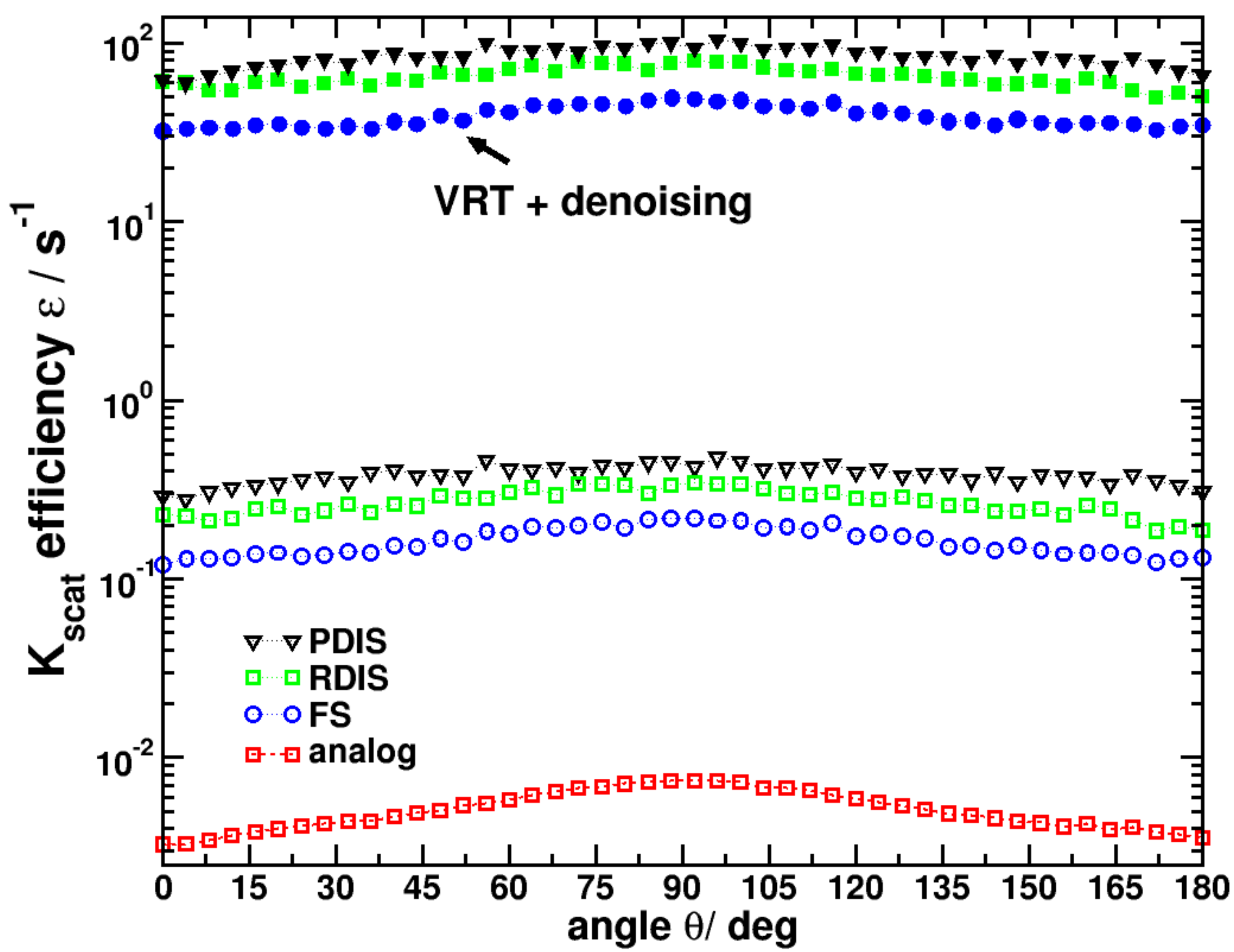
Efficiency gain for 120 kV x-ray beam

Chest phantom: 200 $\times$ 200 $\times$ 200 5 mm voxels, 256 X 256 2 mm pixel screen



Efficiency gain for 120 kV x-ray beam

Chest phantom: 200 × 200 × 200 5 mm voxels, 256 X 256 2 mm pixel screen



FS / ANA =9833
RDIS/ANA=18531
PDIS/ANA=18942

What does this mean?

Analog: $T_{\mathrm{CPU}}(3\%) = 340330\ \mathrm{s} \approx 4\ \mathrm{days}$

no smoothing: $T_{\mathrm{CPU}}(3\%) = 2057.6\ \mathrm{s} = 34\ \mathrm{min}$

smoothing: $T_{\mathrm{CPU}}(3\%) = 18.4\ \mathrm{s}$

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