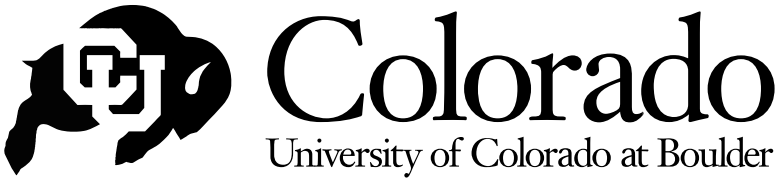
A snapshot of the UNB ray-tracer

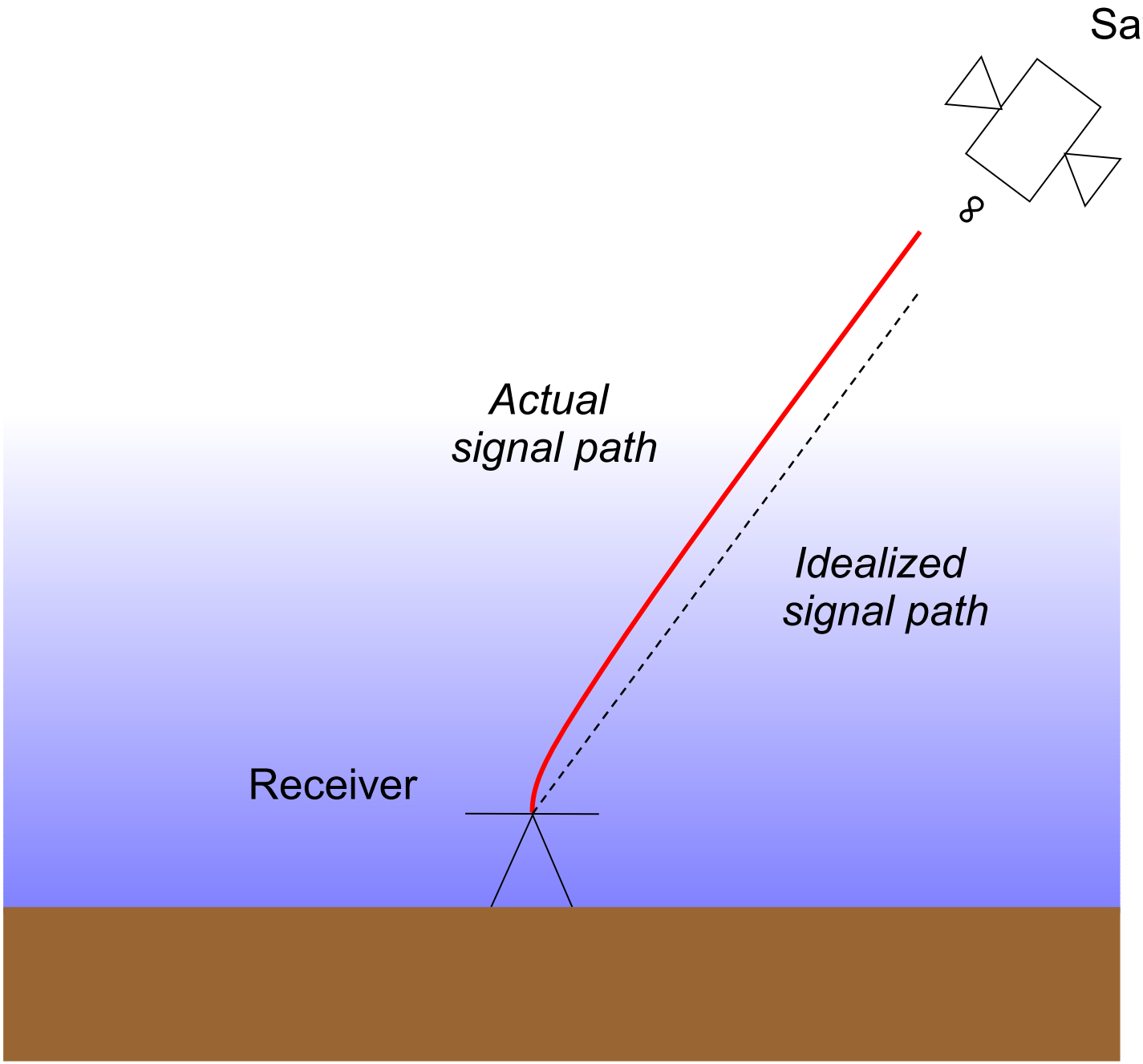
Felipe G. Nievinski



Dept. of Aerospace Engineering Sciences

University of Colorado at Boulder

Workshop on Numerical Weather Models for Space Geodesy Positioning
24-25 Oct. 2011, Dept. of Geodesy and Geomatics Engineering, University of New Brunswick


Satellite
Actual
signal path
Idealized
signal path
Receiver

Outline

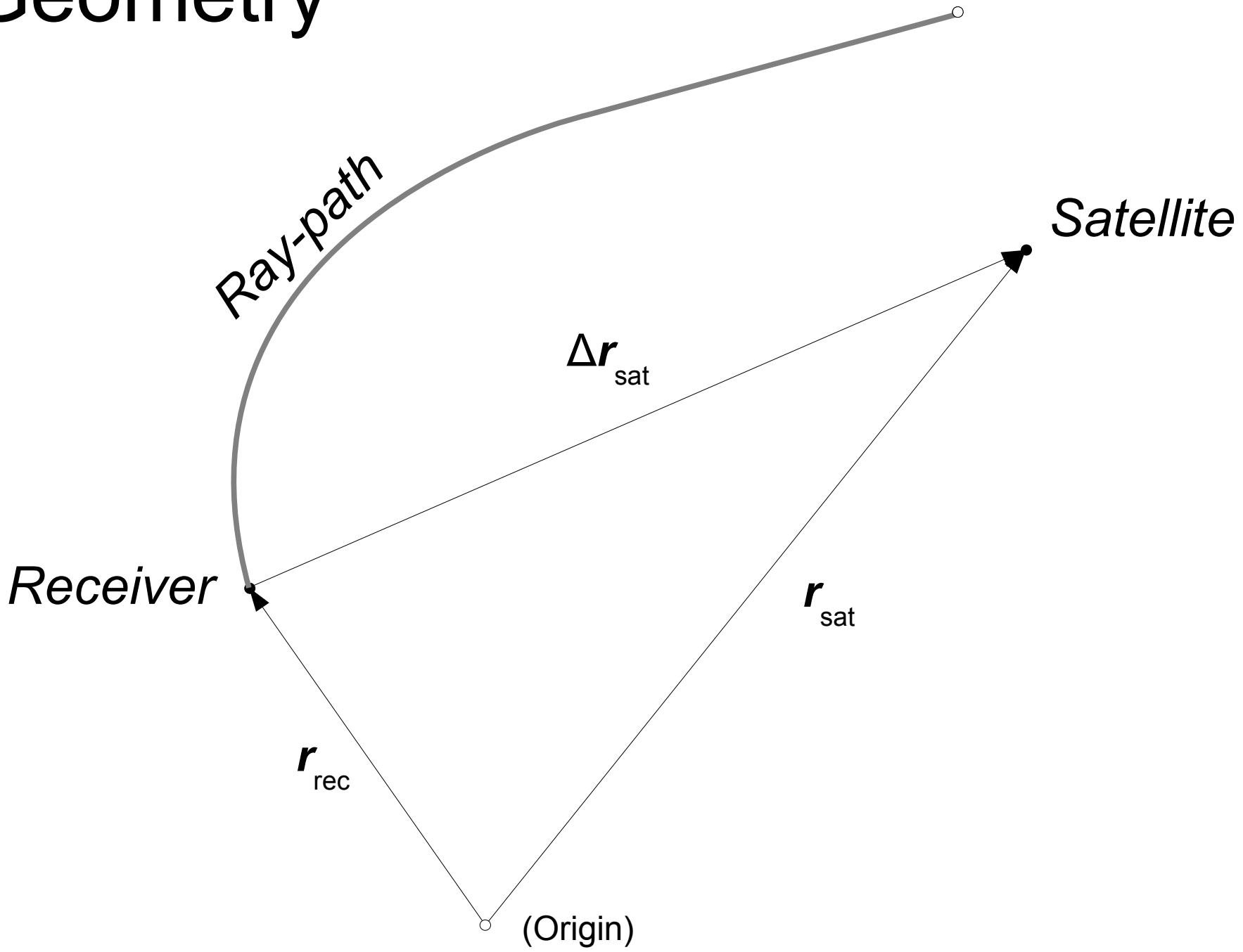
I. Problem statement

II. Ray-tracing options

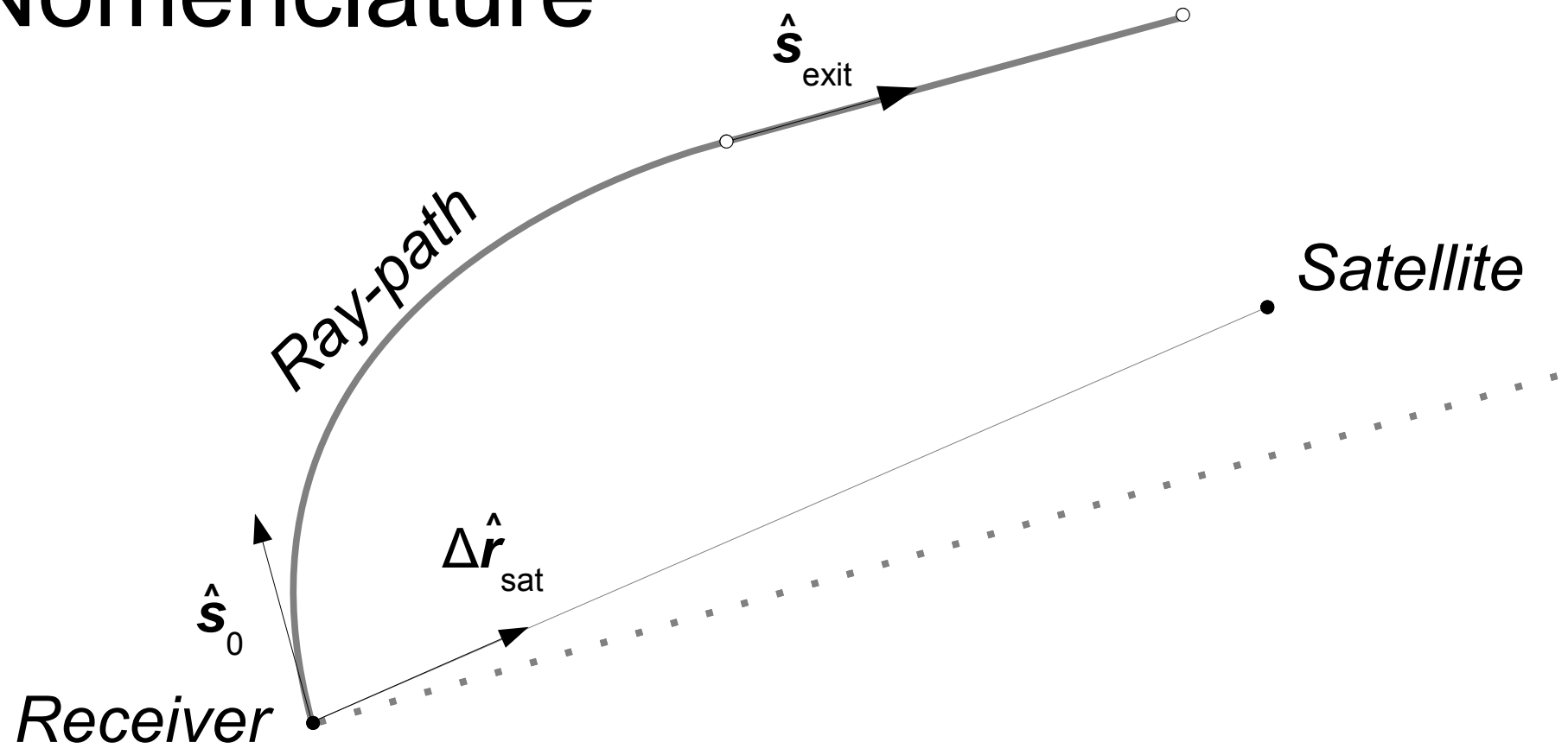
III. Rectified perturbed quadrature

IV. Conclusions

Geometry


Ray-path
Satellite
$\Delta \boldsymbol{r}_{sat}$
Receiver
$\boldsymbol{r}_{sat}$
$\boldsymbol{r}_{rec}$
(Origin)

Nomenclature

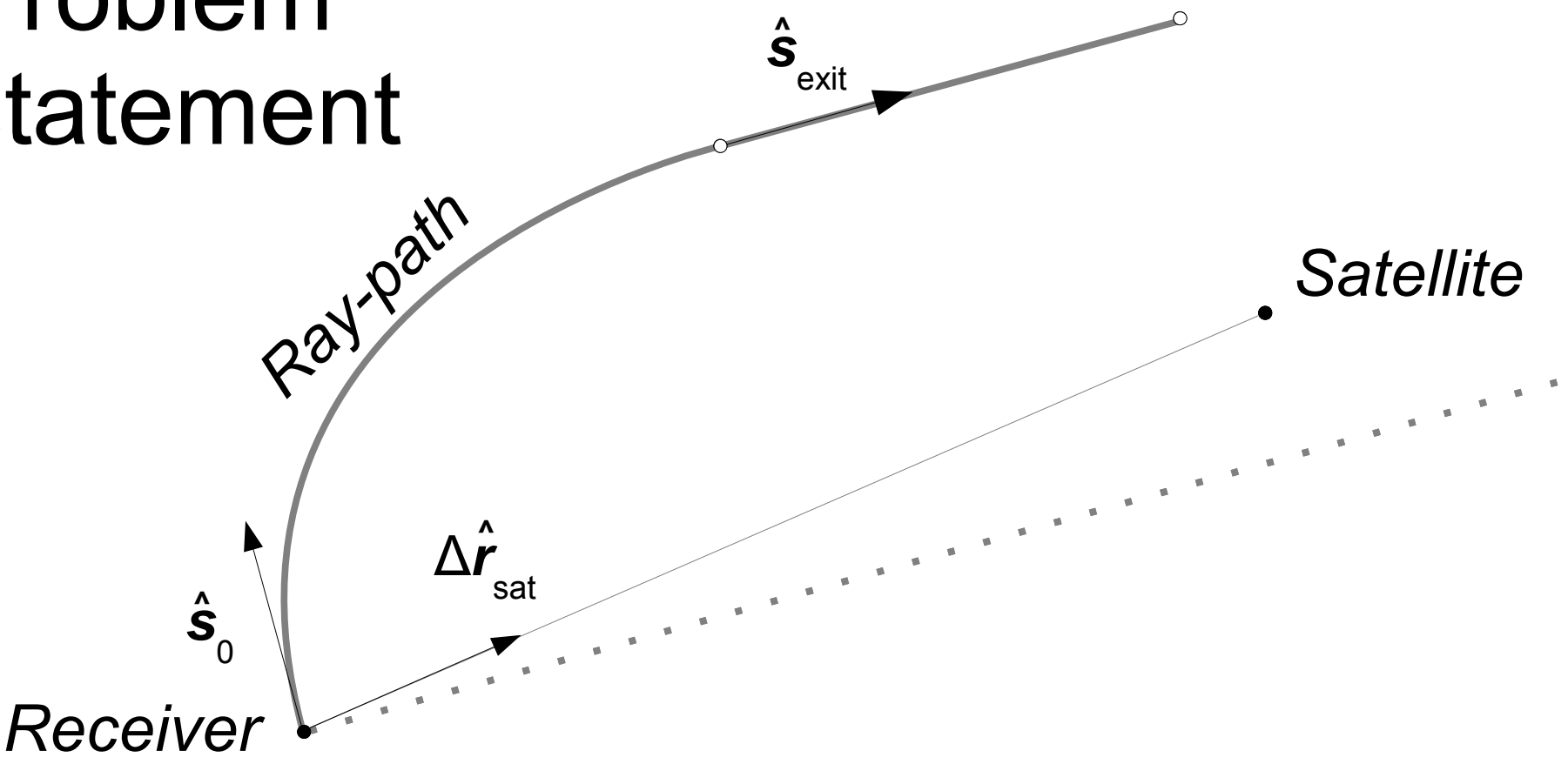


$\hat{s}_0$ *Initial direction*

$\hat{s}_{exit}$ *Exit (pierce, final, outgoing) direction*

$\Delta\hat{r}_{sat}$ *Geometric direction*

Problem statement



$\hat{s}_{exit} = \Delta\hat{r}_{sat}$: *boundary value problem (BVP)*

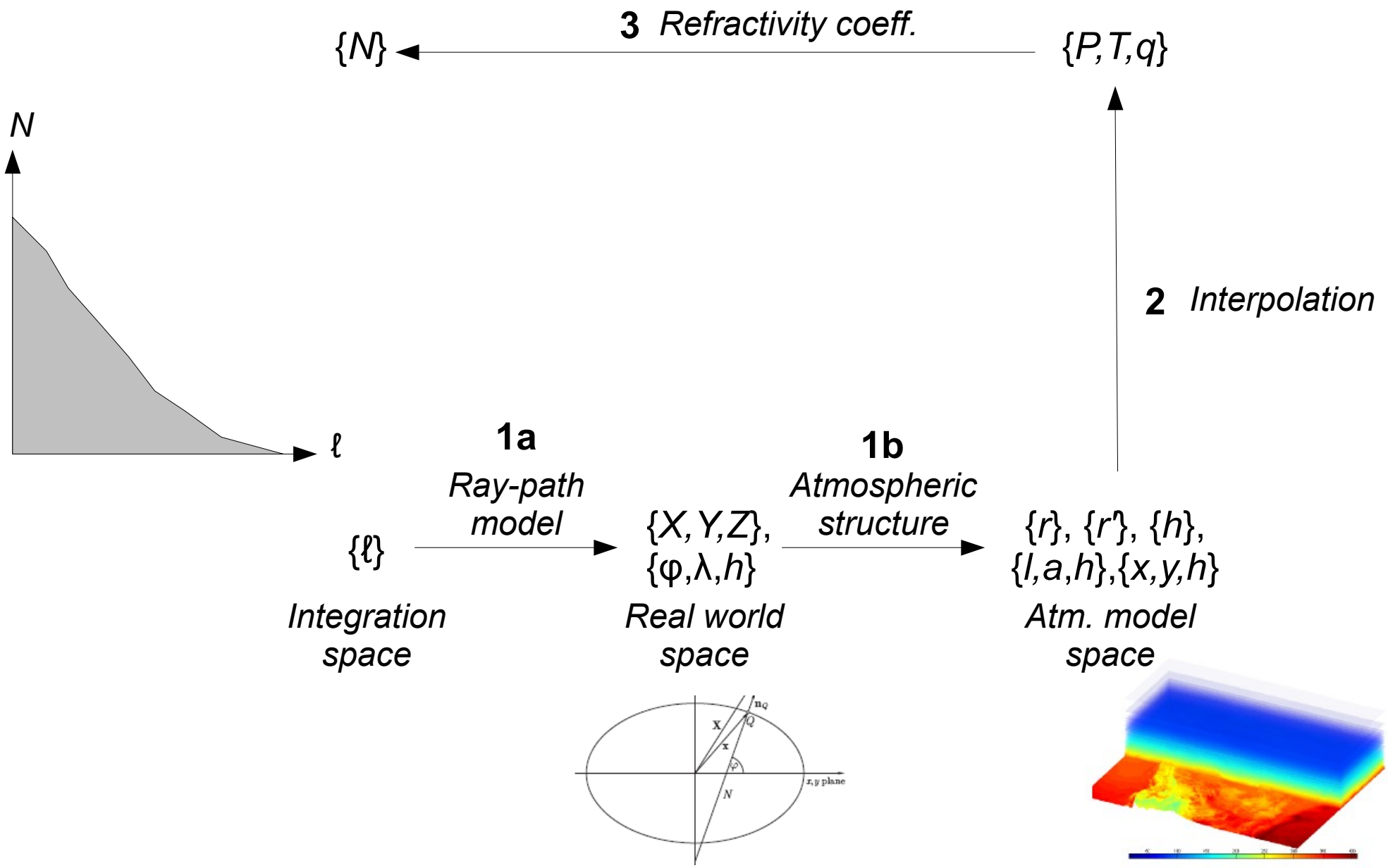
$\hat{s}_0 = \Delta\hat{r}_{sat}$: *initial value problem (IVP)*

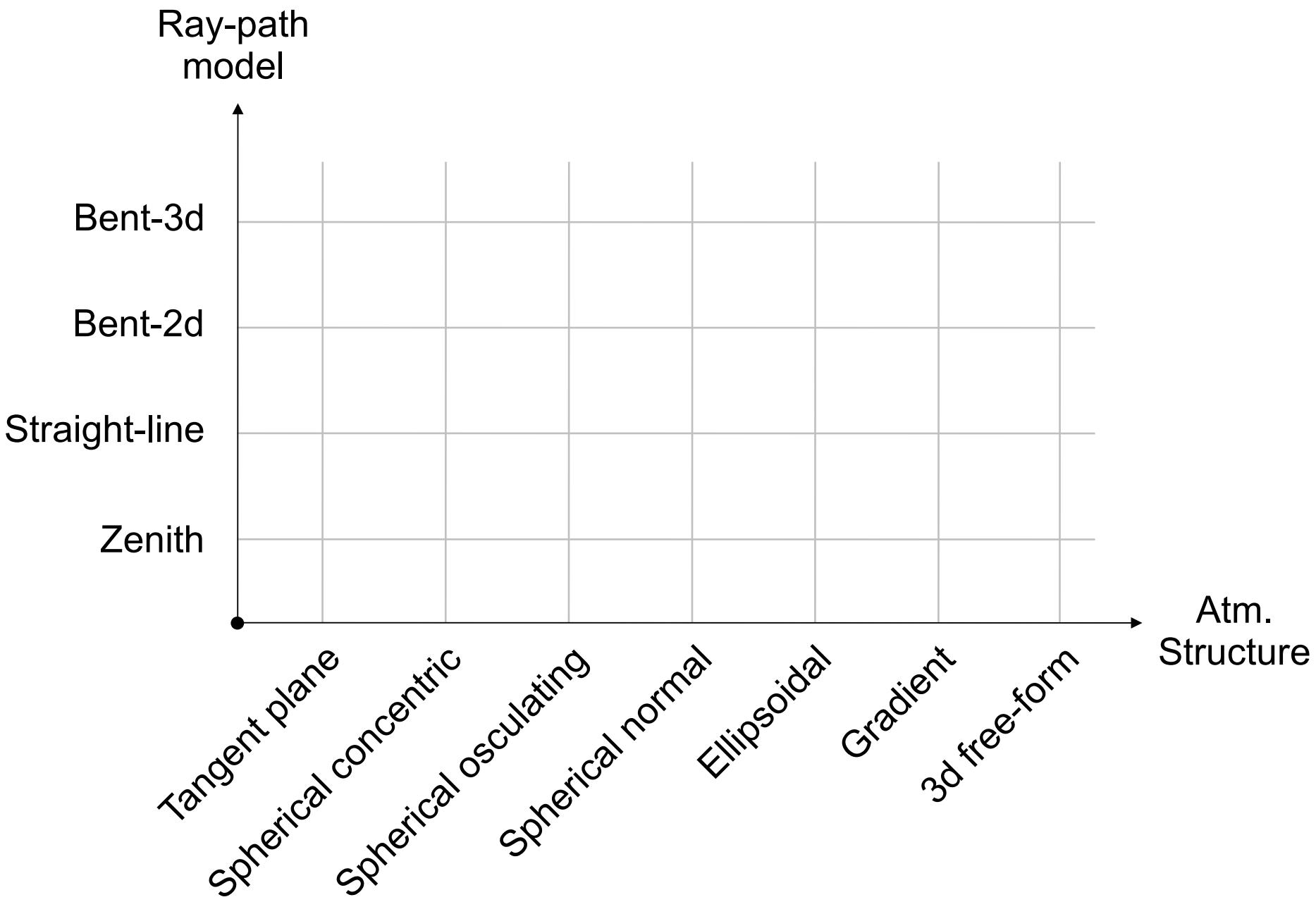
$\hat{s}_0 = \hat{s}_{exit} = \Delta\hat{r}_{sat}$: *straight-line ray-tracing*

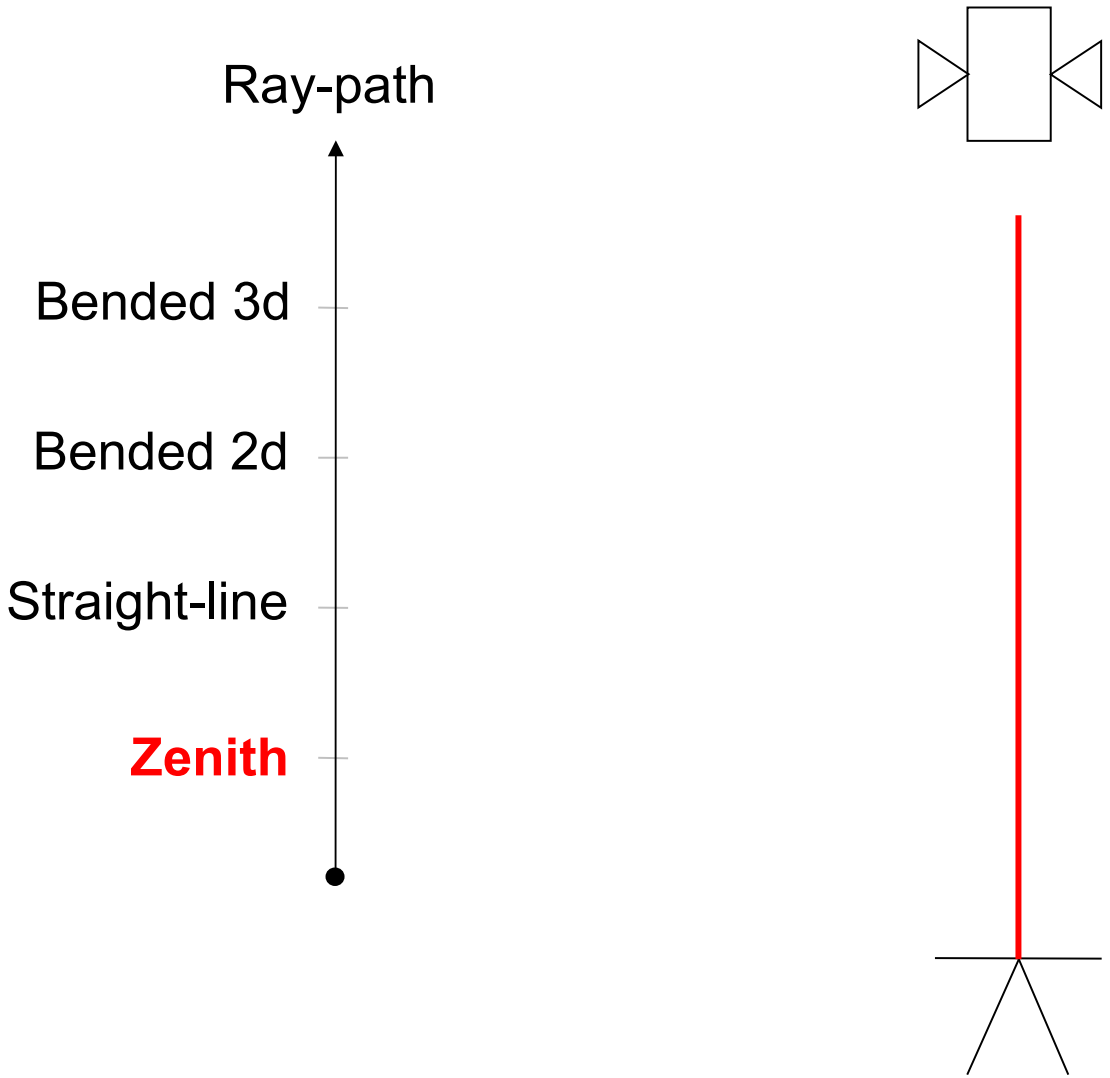
Part II:

Ray-tracing options

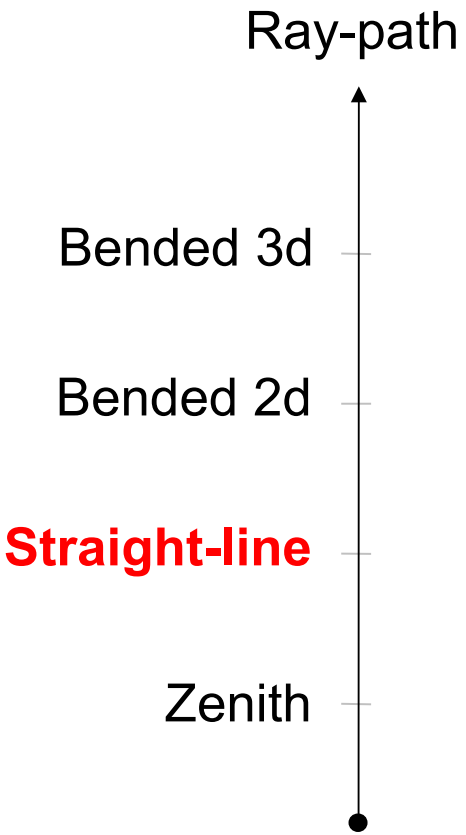
Coordinate spaces

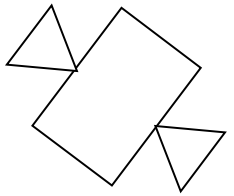


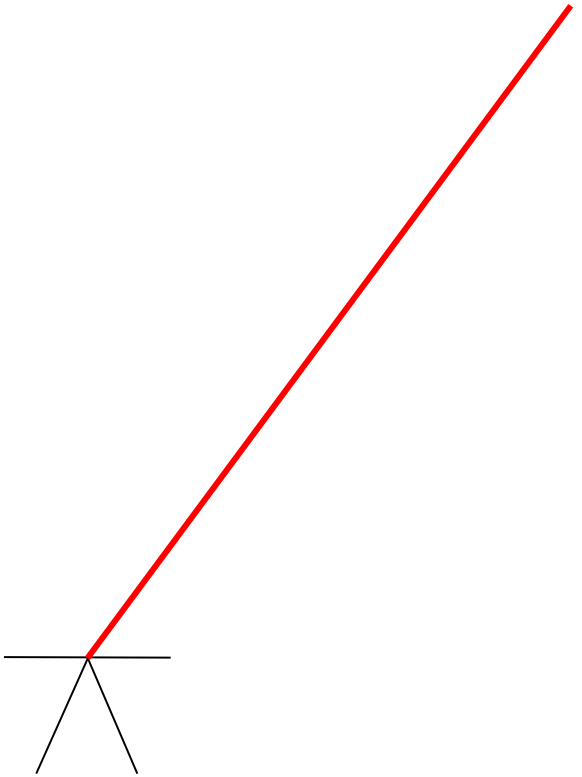

Ray-path model
Bent-3d
Bent-2d
Straight-line
Zenith
Atm. Structure
Tangent plane
Spherical concentric
Spherical osculating
Spherical normal
Ellipsoidal
Gradient
3d free-form



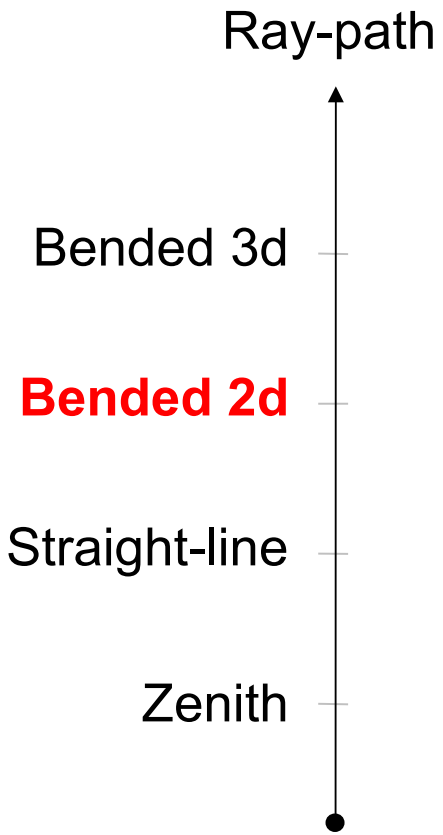
$$\boldsymbol{r} \xleftarrow[\varphi\lambda h]{XYZ} (\varphi_0, \lambda_0, h_0 + \ell)$$

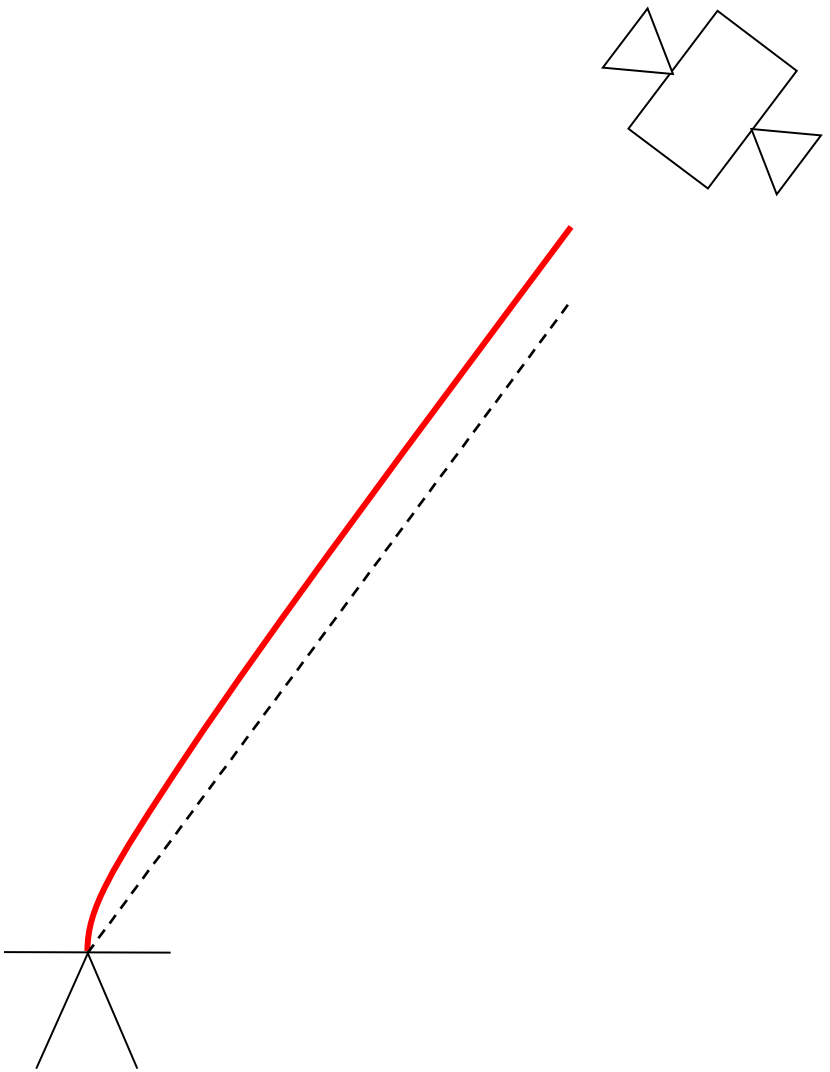




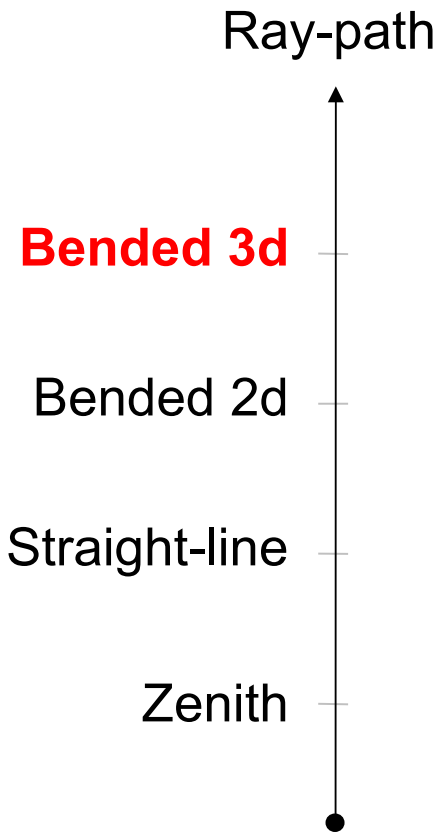


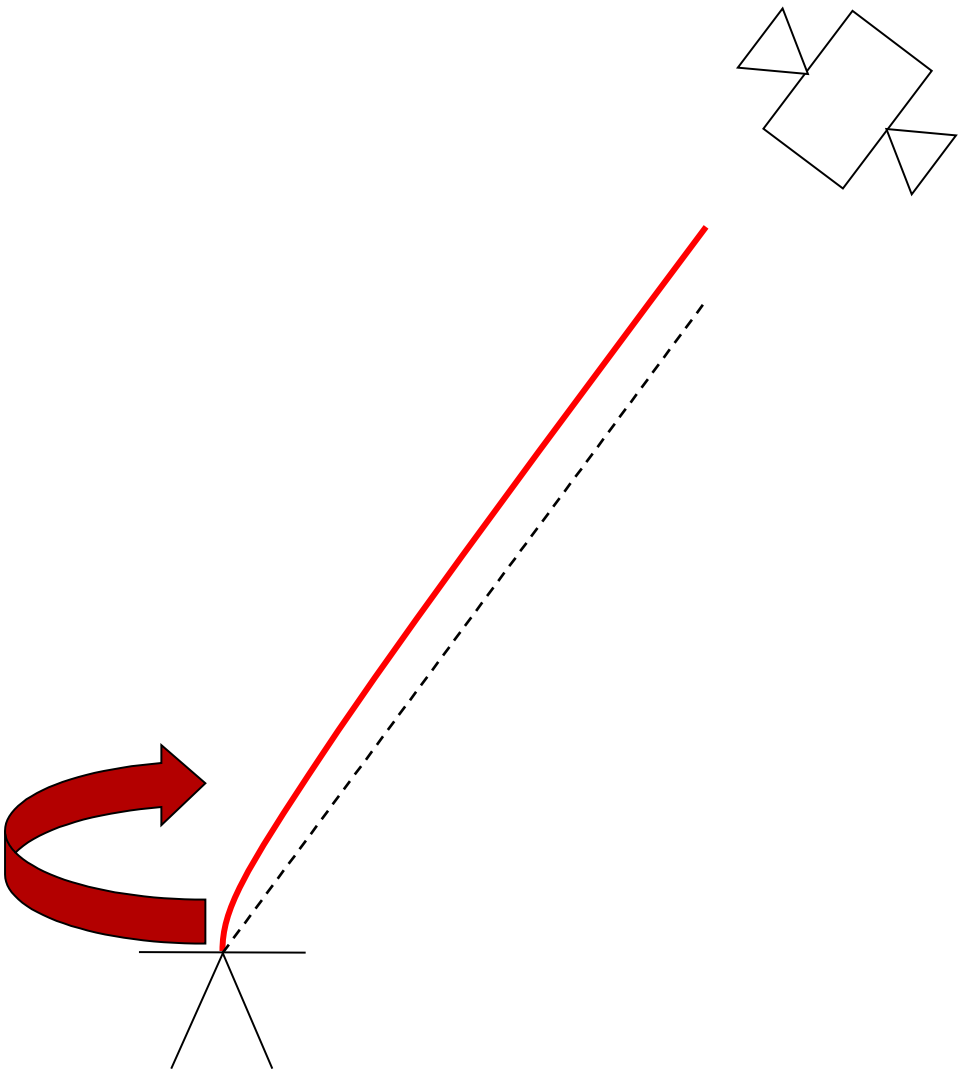
$$\boldsymbol{r} = \boldsymbol{r}_0 + \ell\, \hat{\boldsymbol{s}}_0$$



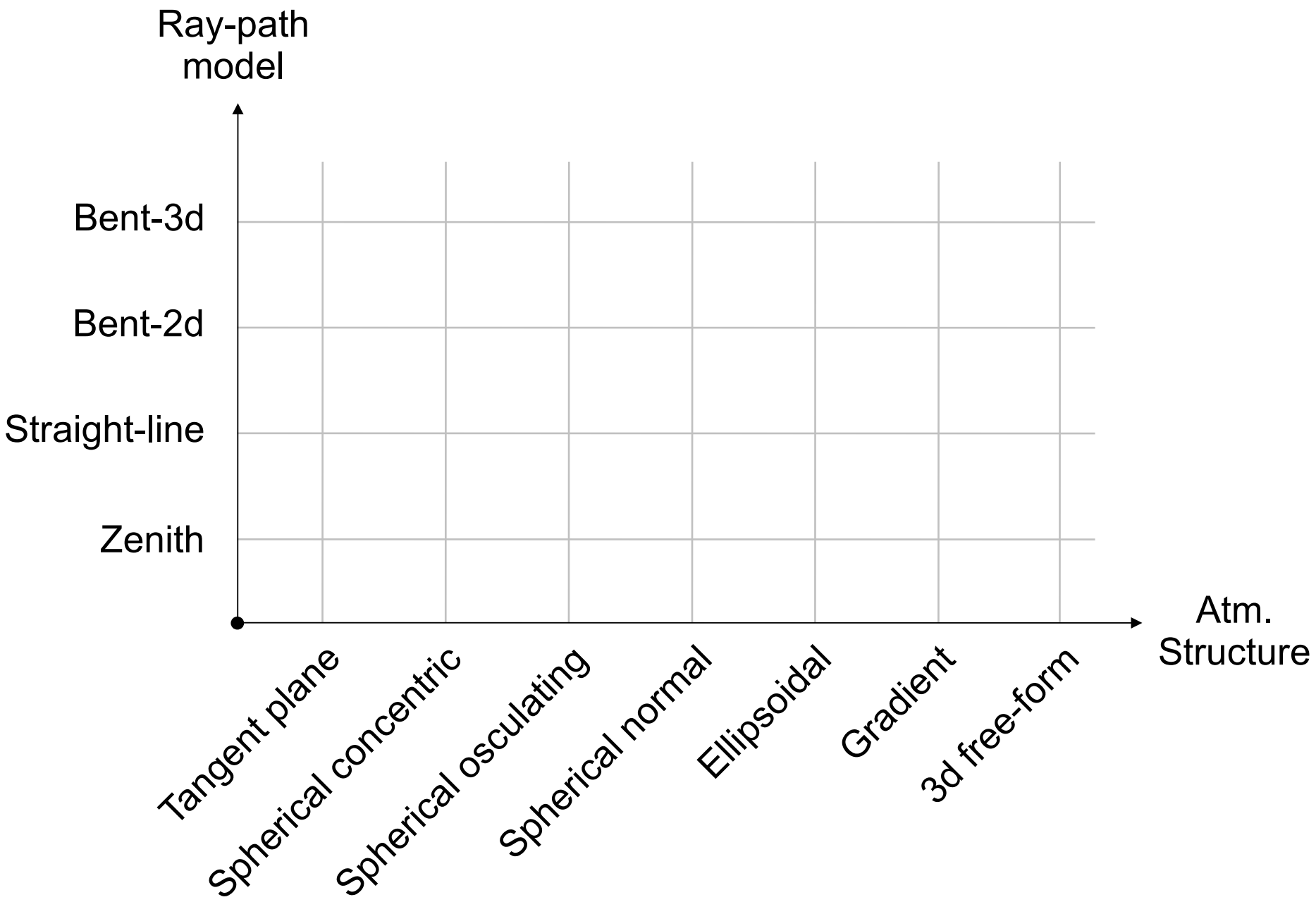


$$\mathrm{d}r' = -\tan(z)\mathrm{d}n/n$$

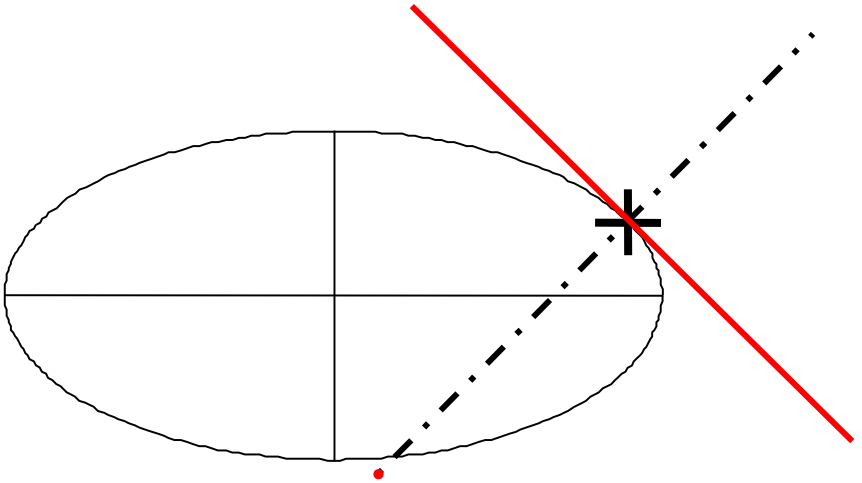


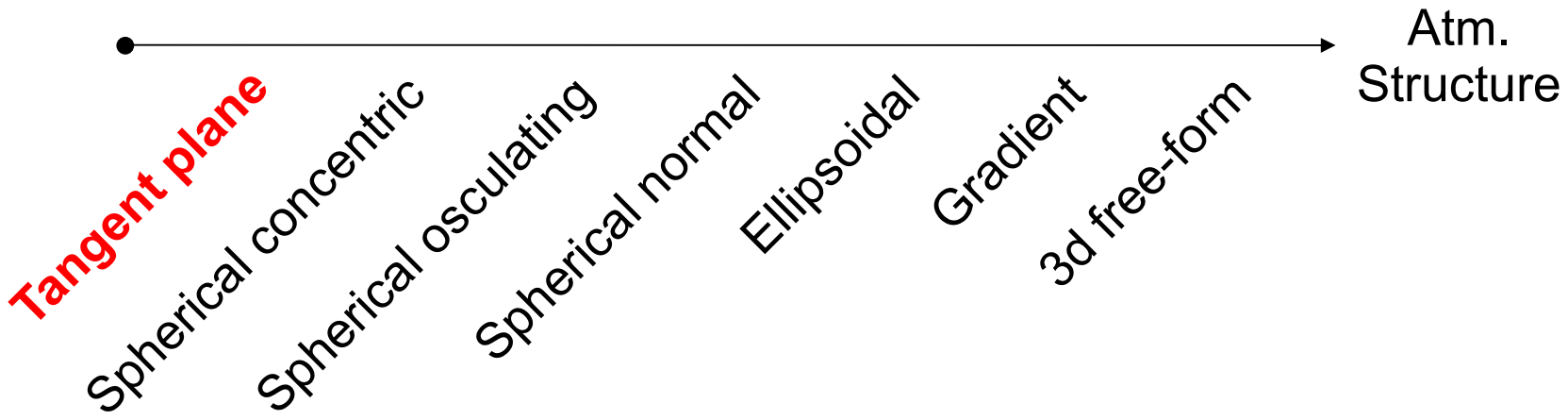


$$\frac{\mathrm{d}}{\mathrm{d}\ell}\left(n\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}\ell}\right) = \boldsymbol{\nabla} n$$


Ray-path model
Bent-3d
Bent-2d
Straight-line
Zenith
Atm. Structure
Tangent plane
Spherical concentric
Spherical osculating
Spherical normal
Ellipsoidal
Gradient
3d free-form

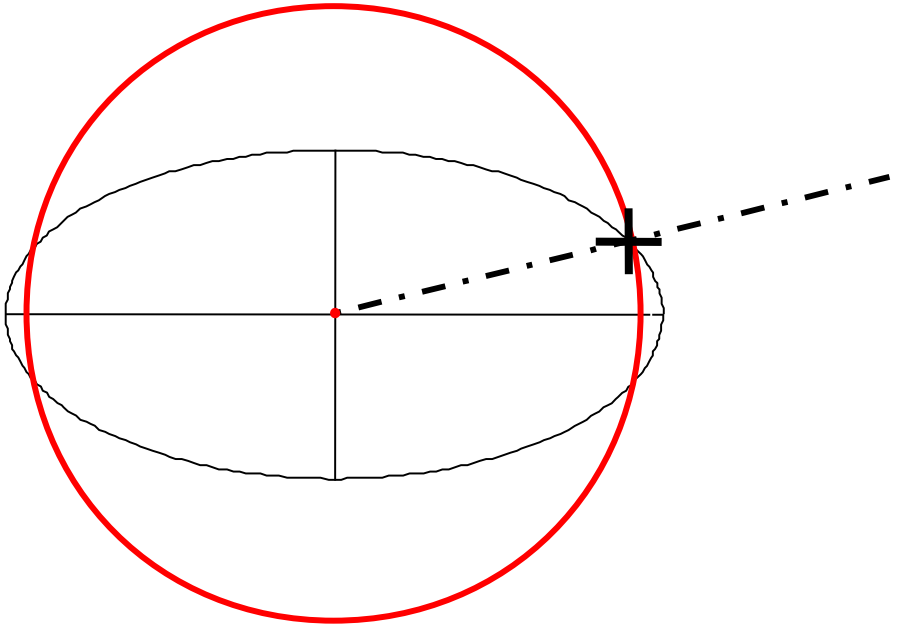
$$v = \mathrm{f}(H)$$

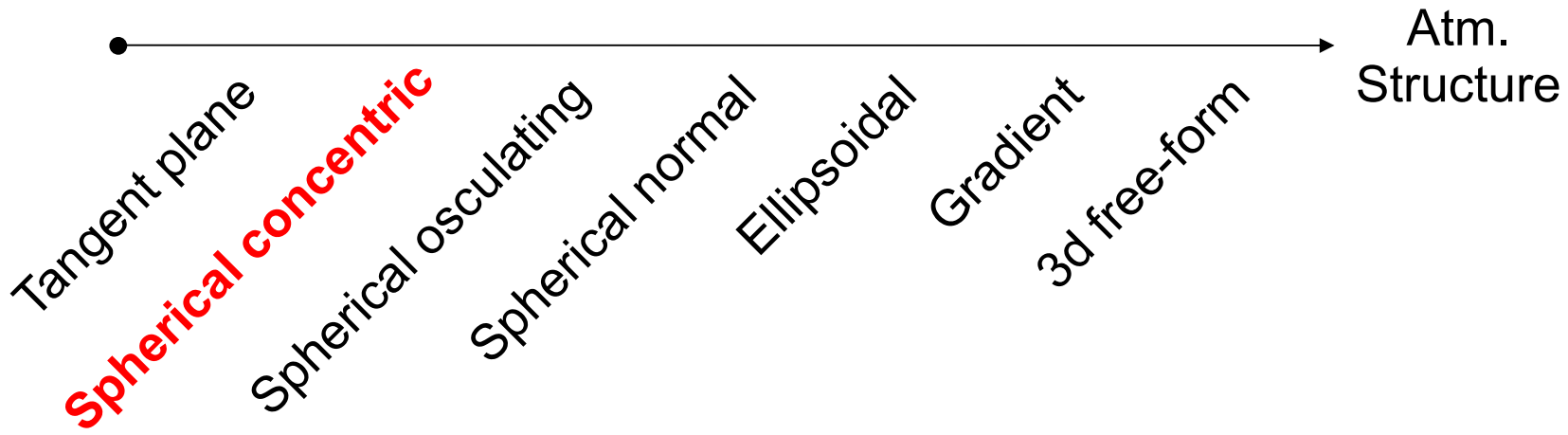



Tangent plane
Spherical concentric
Spherical osculating
Spherical normal
Ellipsoidal
Gradient
3d free-form
Atm. Structure

$$v = \mathrm{f}\,(r)$$

$$r = |\boldsymbol{r}|$$





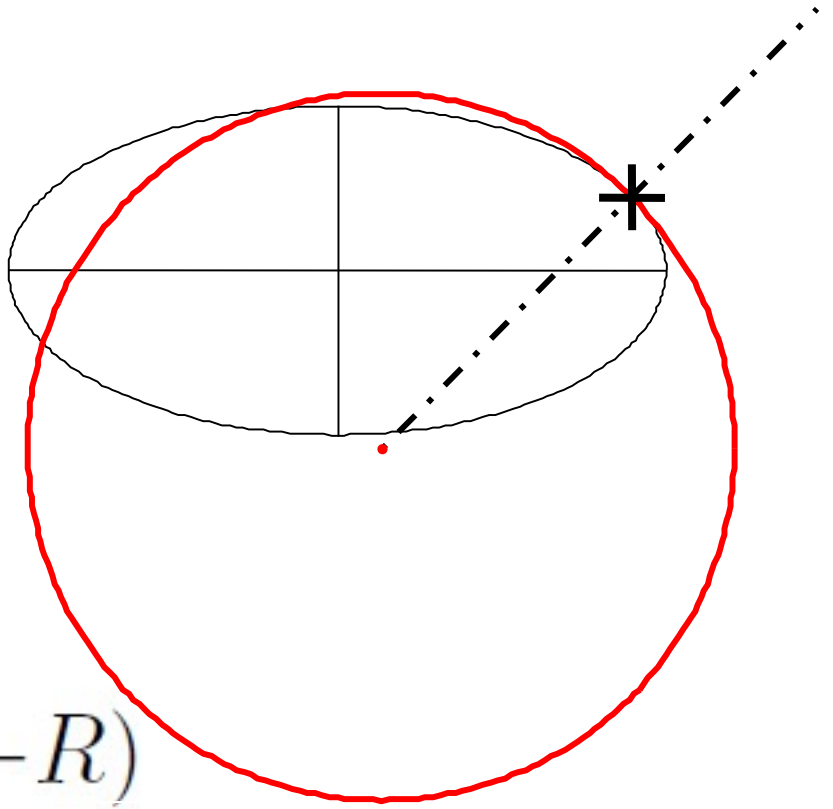
$$v = \mathrm{f}\left(r'\right)$$

$$r' = \left|\boldsymbol{r}'\right|$$

$$\boldsymbol{r}' \equiv \boldsymbol{r} + \boldsymbol{r}_c$$

$$R = \sqrt{MN}$$

$$\boldsymbol{r}_c \xleftarrow[\varphi\lambda h]{XYZ} (\varphi_0, \lambda_0, h = -R)$$



Atm. Structure

Tangent plane

Spherical concentric

Spherical osculating

Spherical normal

Ellipsoidal

Gradient

3d free-form

Azimuthally symmetric

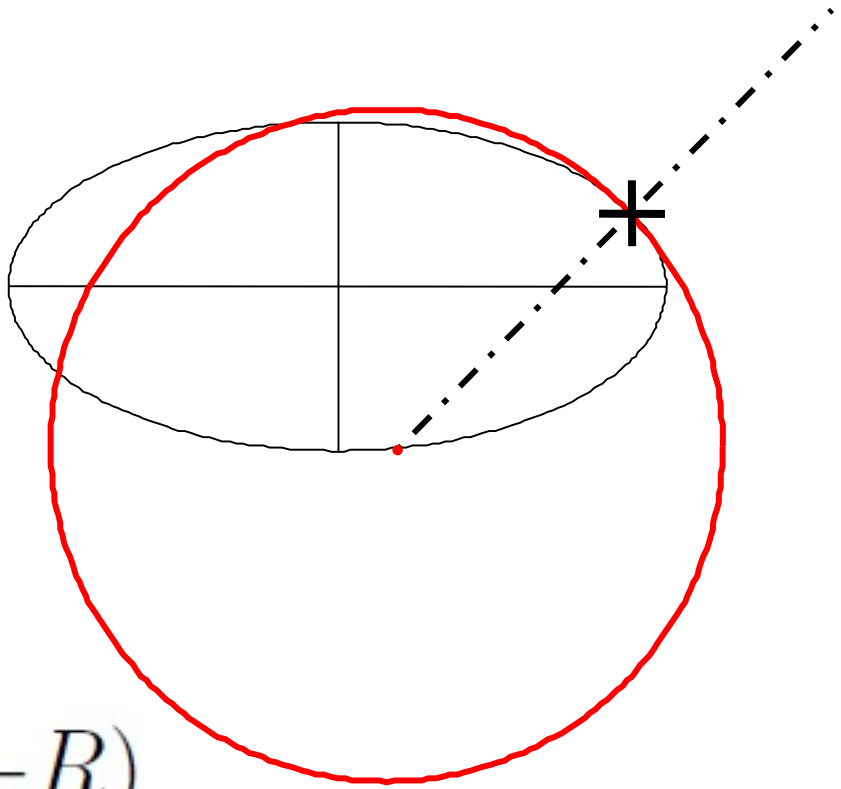
$$v = \mathrm{f}\left(r'\right)$$

$$r' = \left|\boldsymbol{r}'\right|$$

$$\boldsymbol{r}' \equiv \boldsymbol{r} + \boldsymbol{r}_c$$

$R = \text{const.}$, $R = M$, etc.

$$\boldsymbol{r}_c \xleftarrow[\varphi\lambda h]{XYZ} (\varphi_0, \lambda_0, h = -R)$$



Atm. Structure

Tangent plane

Spherical concentric

Spherical osculating

Spherical normal

Ellipsoidal

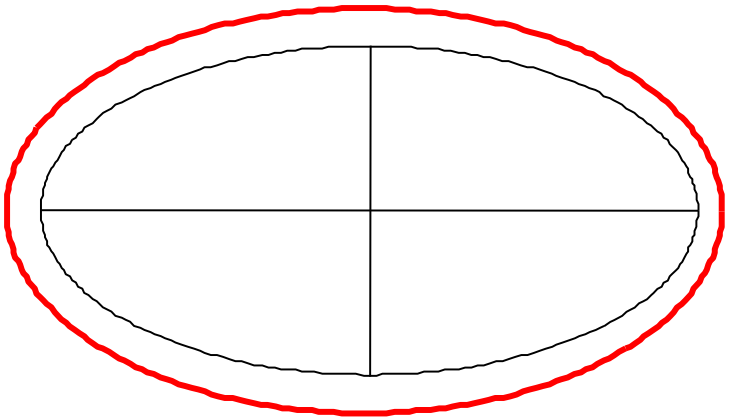
Gradient

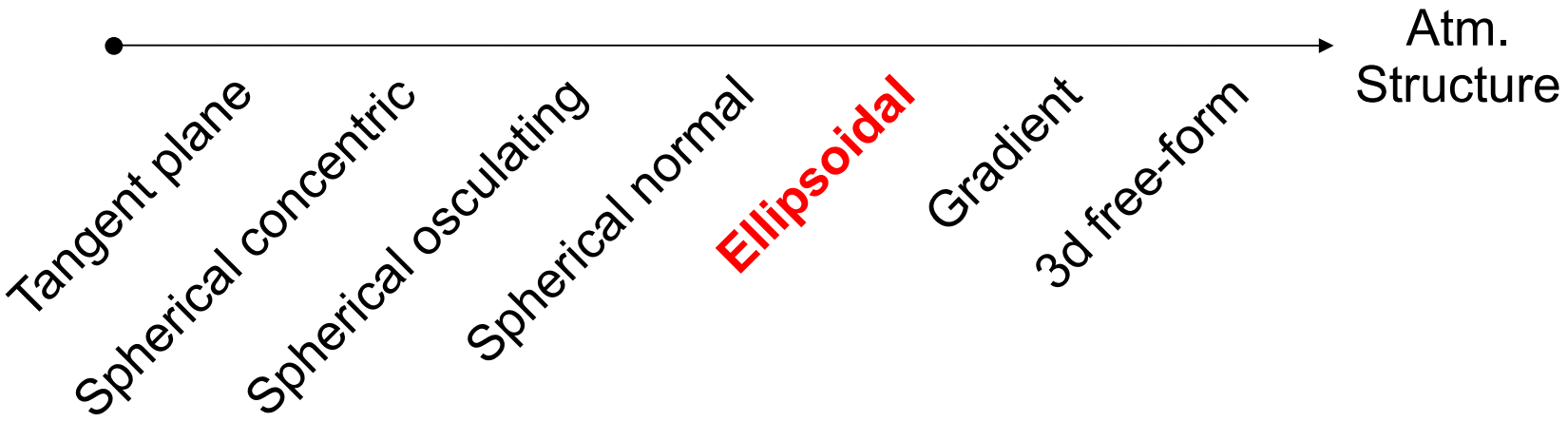
3d free-form

Sph. normal radii:
- Constant
- Meridional
- Gaussian (= osc.)
- Eulerian (≈ ell.)

Azimuthally symmetric, too

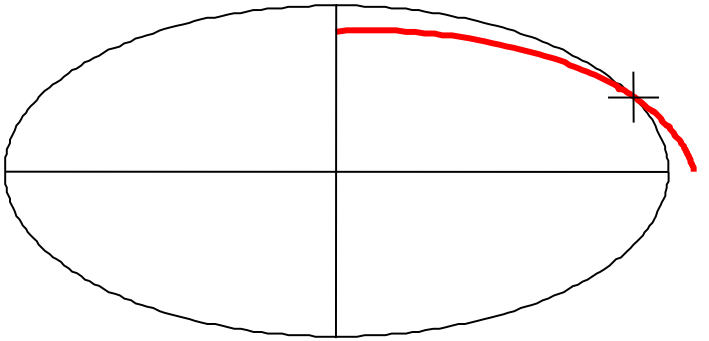
$$v = \mathrm{f}\,(h)$$



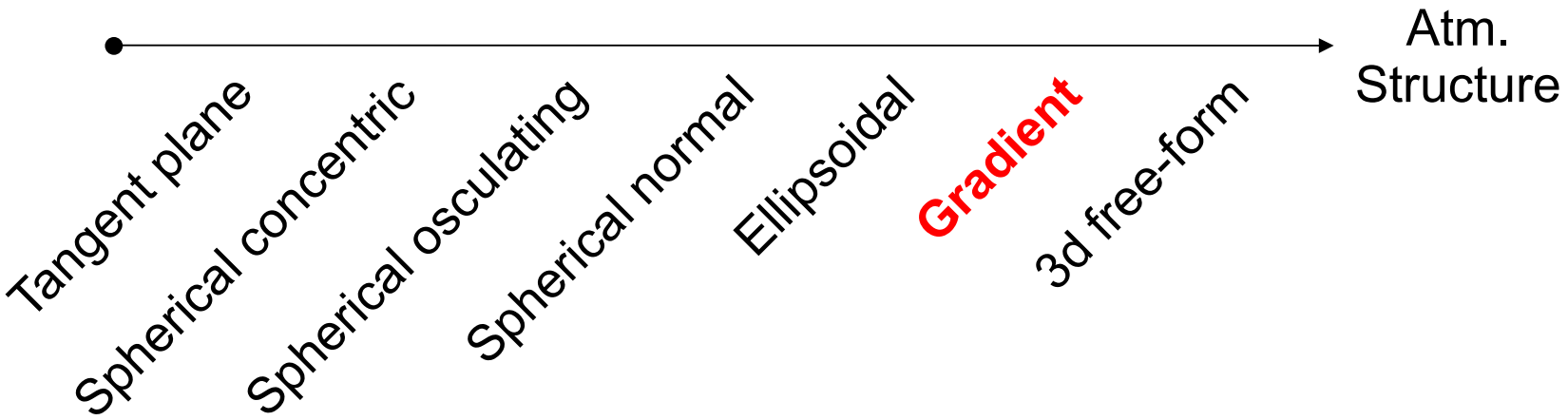


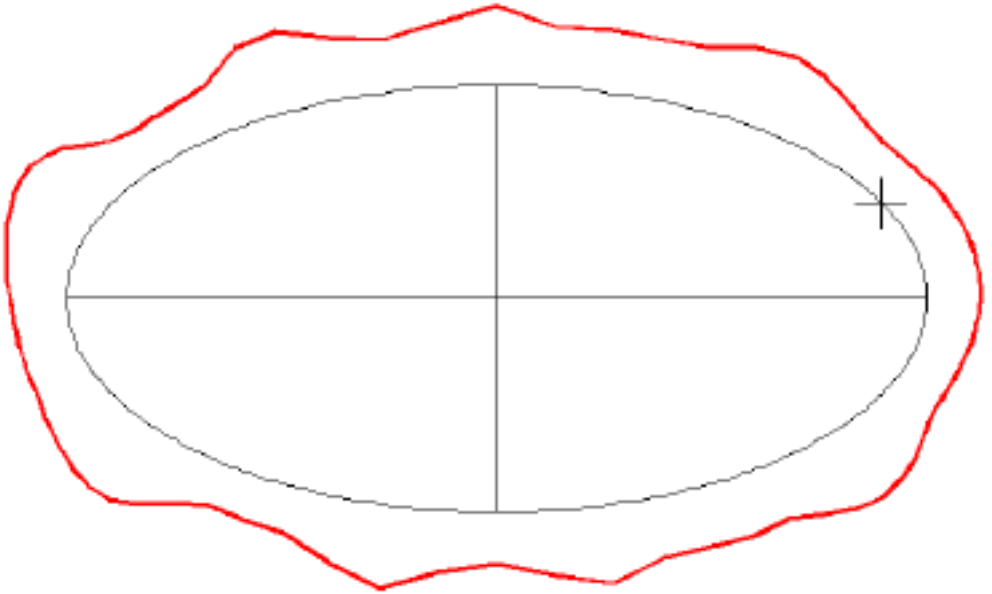
Up till now: profile-based struct. (1D interpolation)

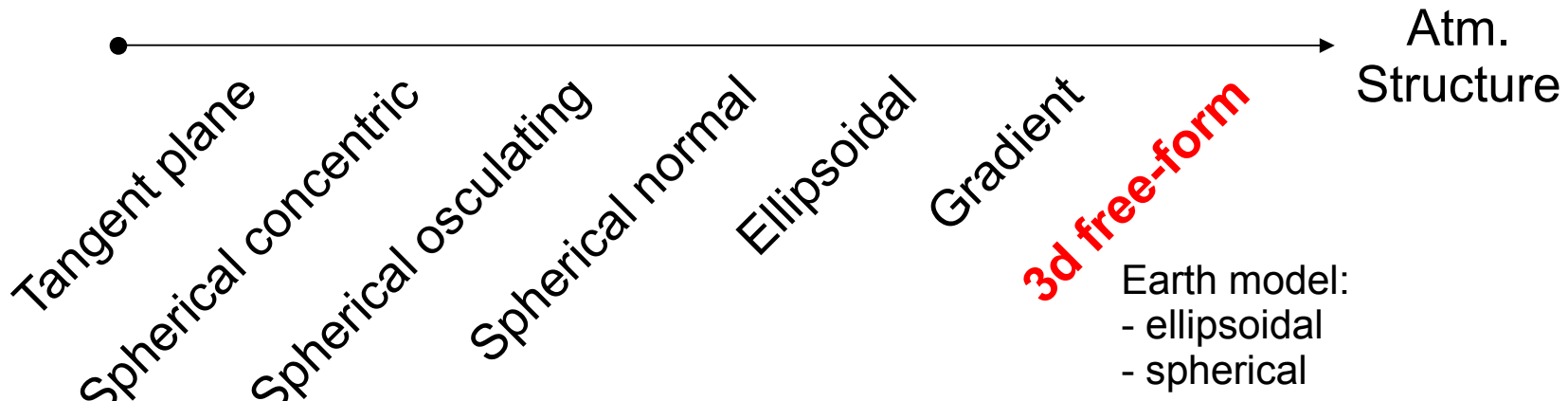
$$v = \mathrm{f}_0(h) + \mathrm{f}_{\boldsymbol{\nabla}_\mathrm{H}}(\varphi, \lambda, h)$$



$$\mathrm{f}_{\boldsymbol{\nabla}_\mathrm{H}}(\varphi, \lambda, h) = l \left(\sin a \left. \frac{\partial v_0}{\partial x} \right|_h + \cos a \left. \frac{\partial v_0}{\partial y} \right|_h \right)$$







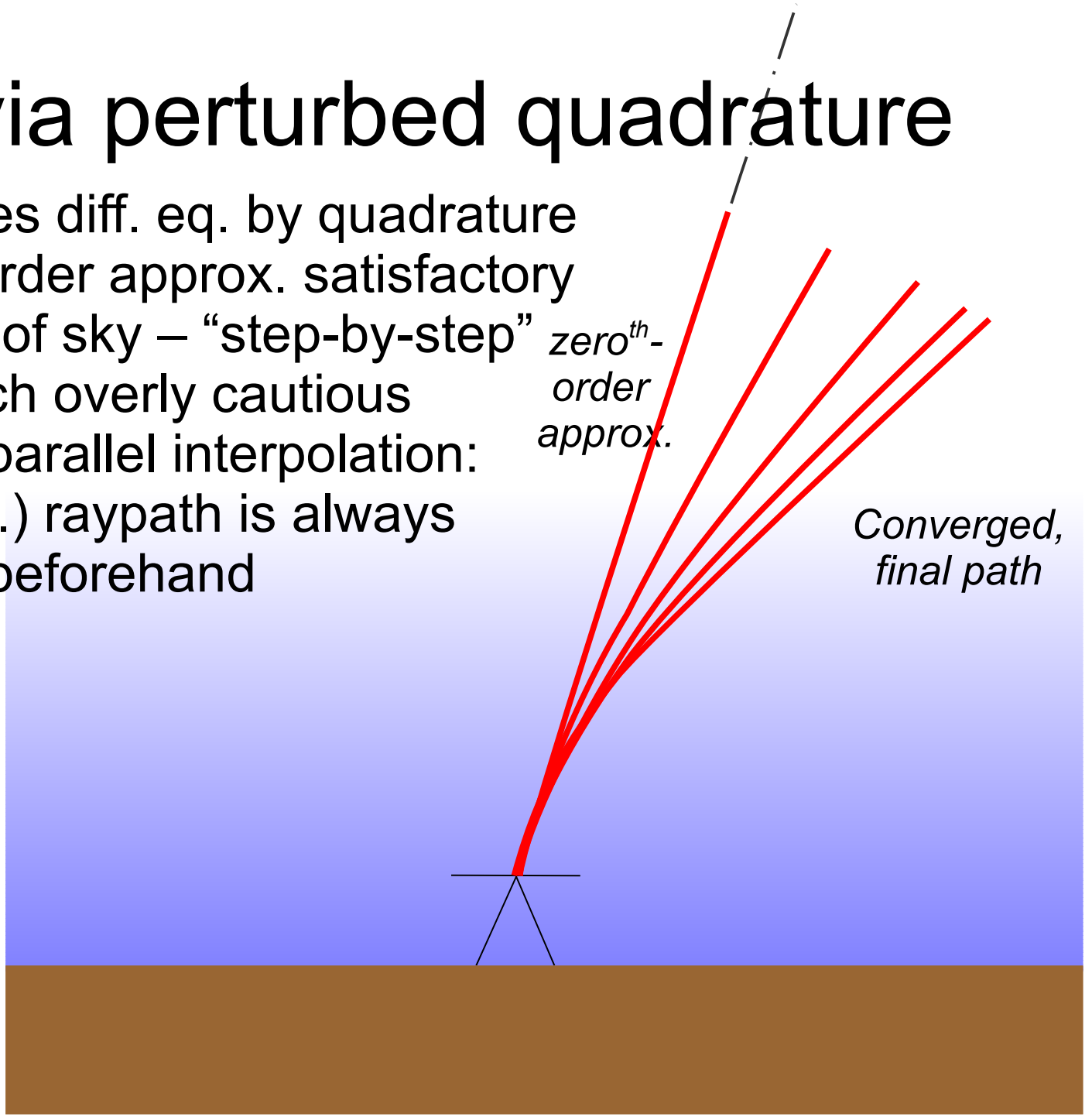
3D interpolation: slower

Part III:

Rectified perturbed quadrature

IVP via perturbed quadrature

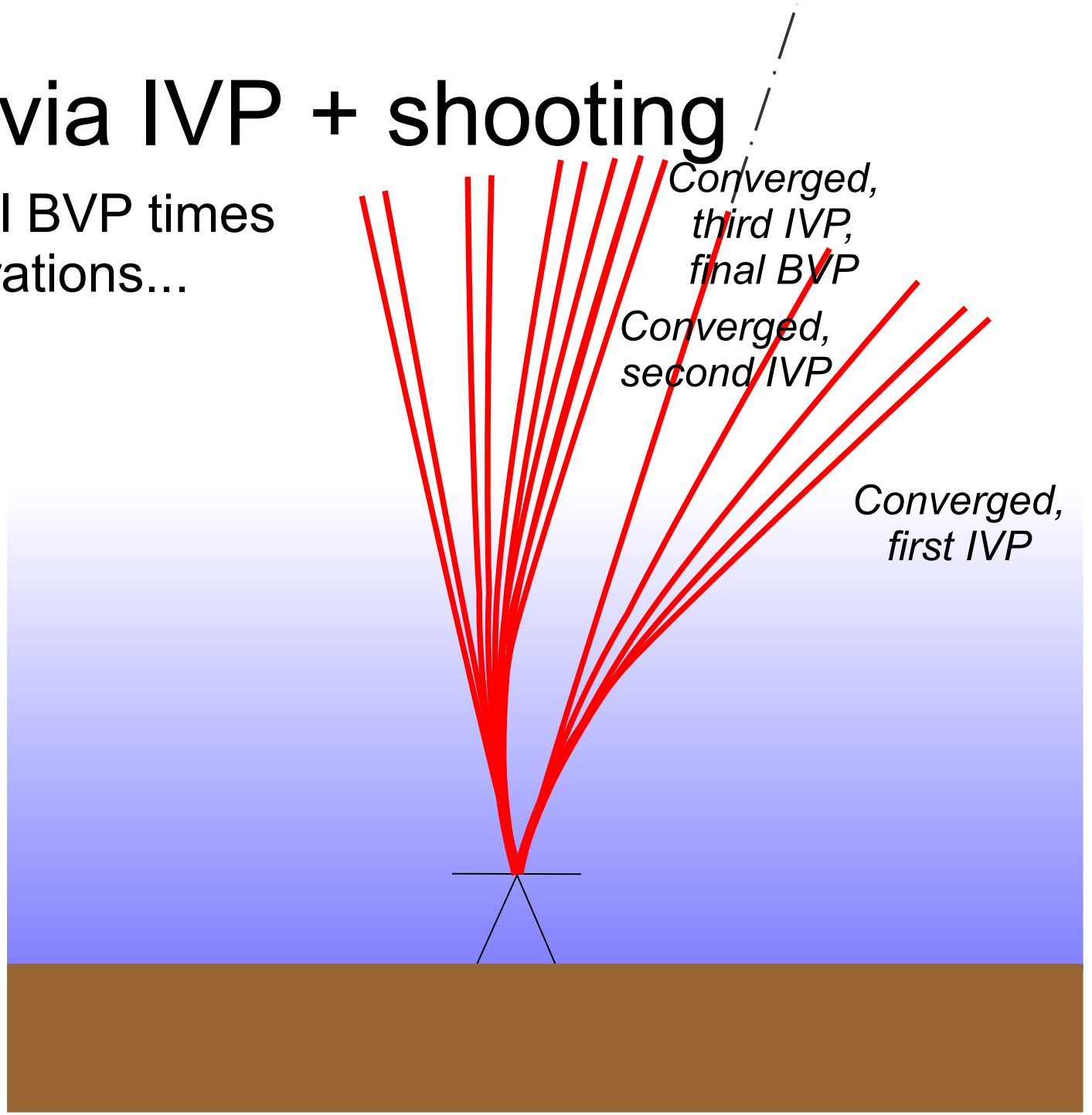
- Replaces diff. eq. by quadrature
- Zeroth order approx. satisfactory in most of sky – "step-by-step" approach overly cautious
- Allows parallel interpolation: (approx.) raypath is always known beforehand



$$\hat{\boldsymbol{s}}_0 = \Delta\hat{\boldsymbol{r}}_{sat} \; : IVP$$

BVP via IVP + shooting

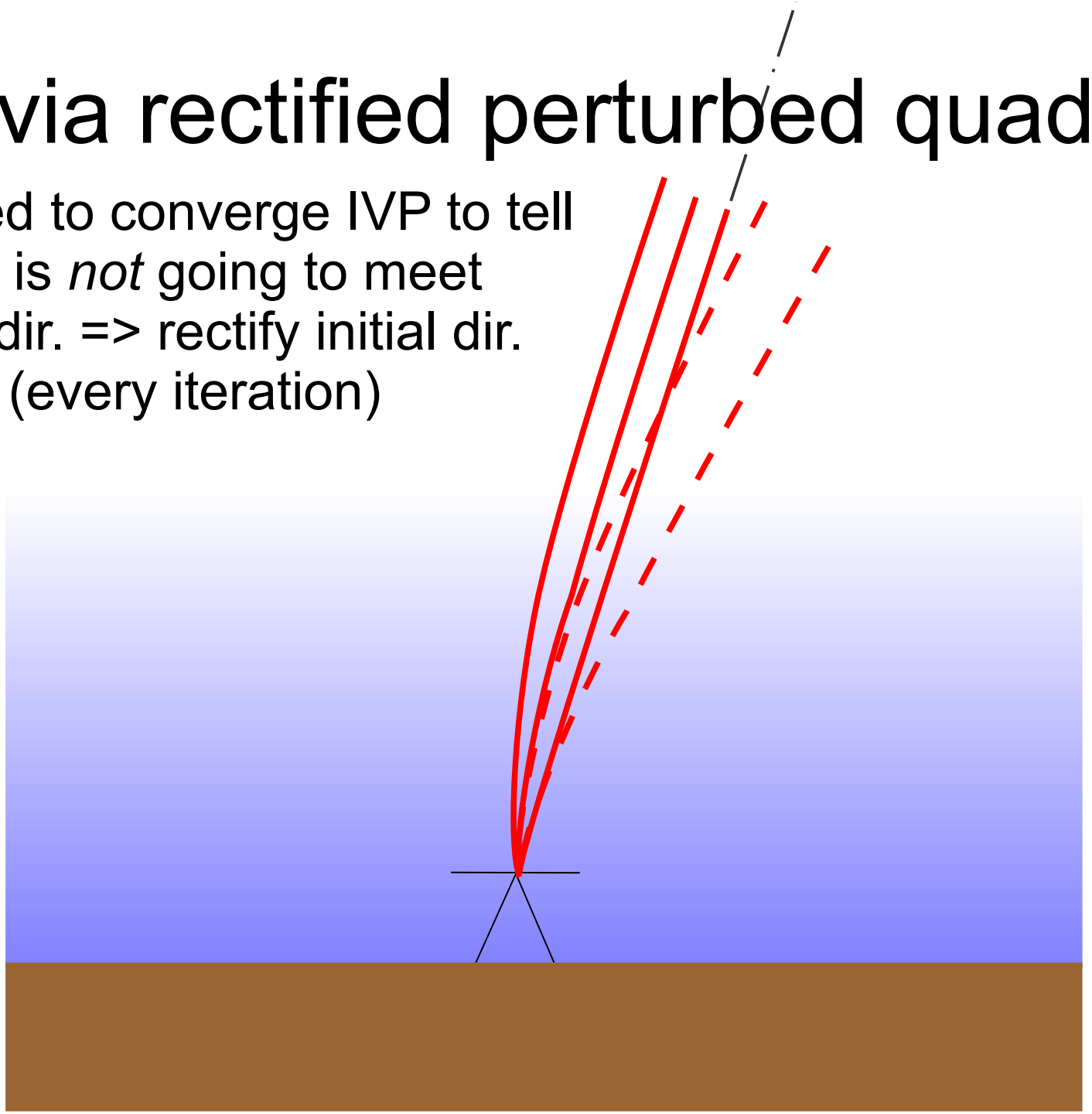
- Several BVP times IVP iterations...



$\hat{\boldsymbol{s}}_{exit} = \Delta\hat{\boldsymbol{r}}_{sat}$: BVP

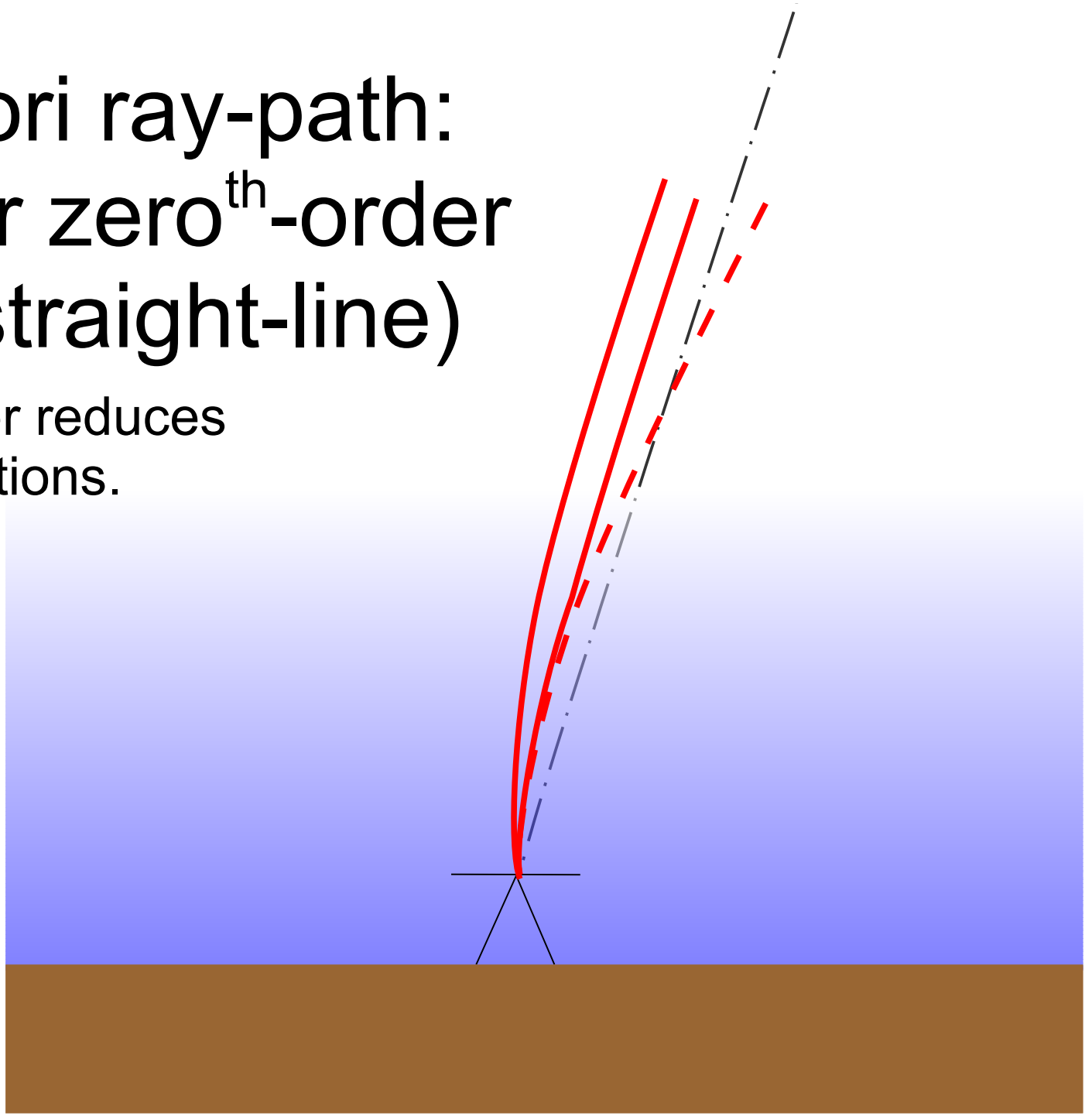
BVP via rectified perturbed quadrature

- No need to converge IVP to tell exit dir. is *not* going to meet geom. dir. => rectify initial dir. sooner (every iteration)



A priori ray-path: better zeroth-order (vs. straight-line)

- Further reduces # iterations.



Part IV:

Conclusions

Summary

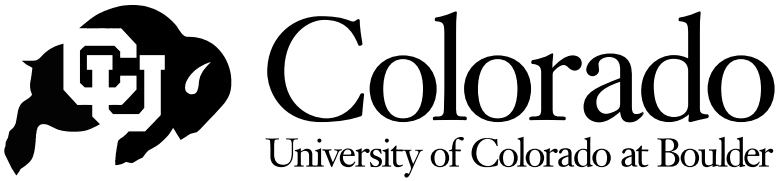
- There are three coordinates spaces involved:
  - Integration, real-world, and NWM's.
  - Ray-path model converts along-path distance to real-world position
  - Atmospheric structure locates real-word position inside the NWM
- There is more than one (reasonable) way of doing atmospheric ray-tracing
  - Trade-off between realism and processing speed.
  - Recommendation:
    - *Bent-2D ray-path and spherical oscullating atm. structure*

Food for thought

- NWM resolution
  - Spatial: global vs. regional vs. local
  - Temporal: 3-hourly snapshots vs. 15-min integration
- NWM Earth model: spherical vs. ellipsoidal
- Deviations from hydrostatic equilibrium
  - Non-hydrostatic models or GPS-equipped radiosondes
- Errorbars for raytraced slant delays & slant factors
  - NWM own errorbars and their propagation in ray-tracing
- Refractivity coefficient values: IUGG update?
- Radio occultation: cross-fertilization of ideas?

A snapshot of the UNB ray-tracer

Felipe G. Nievinski



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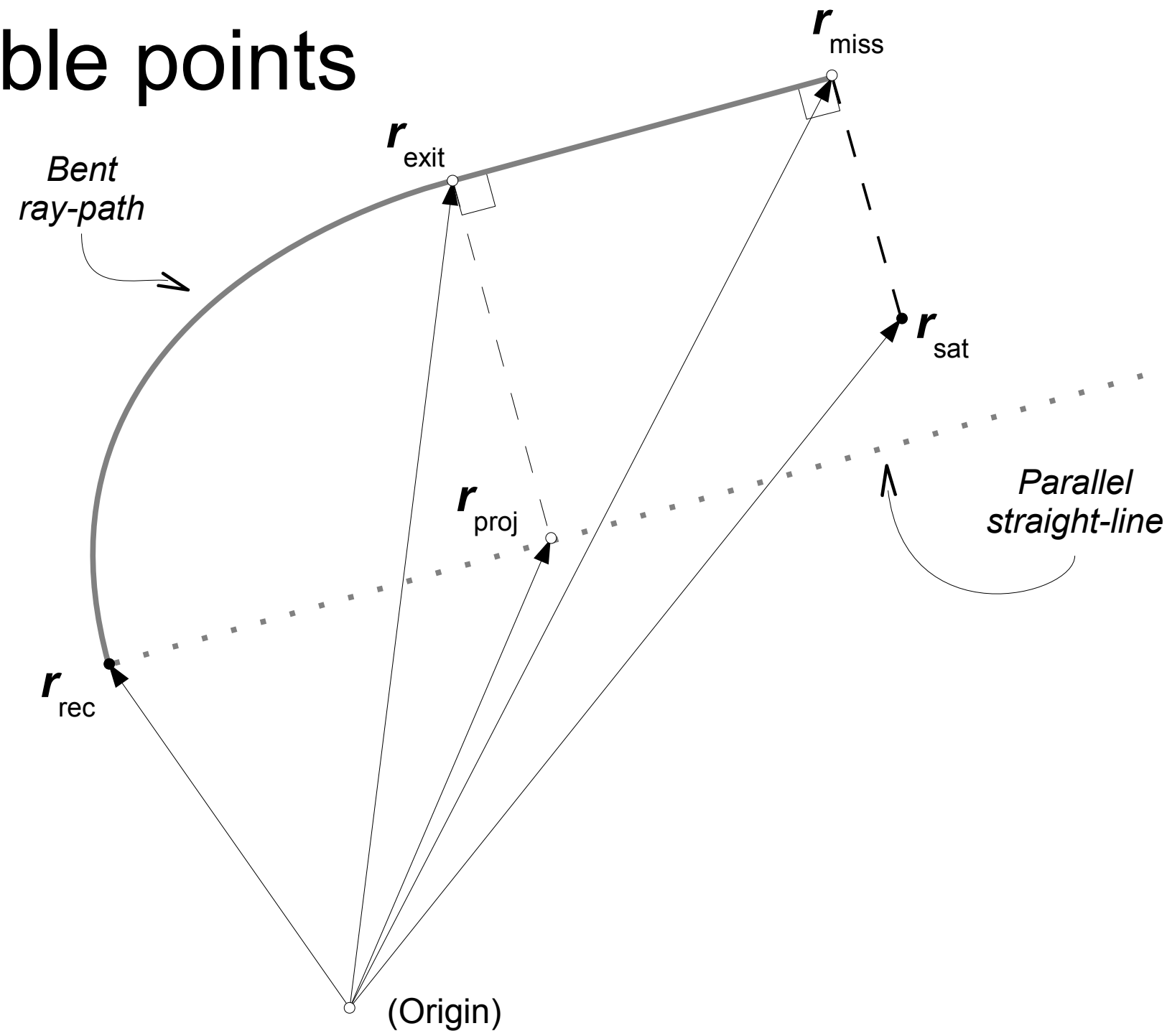
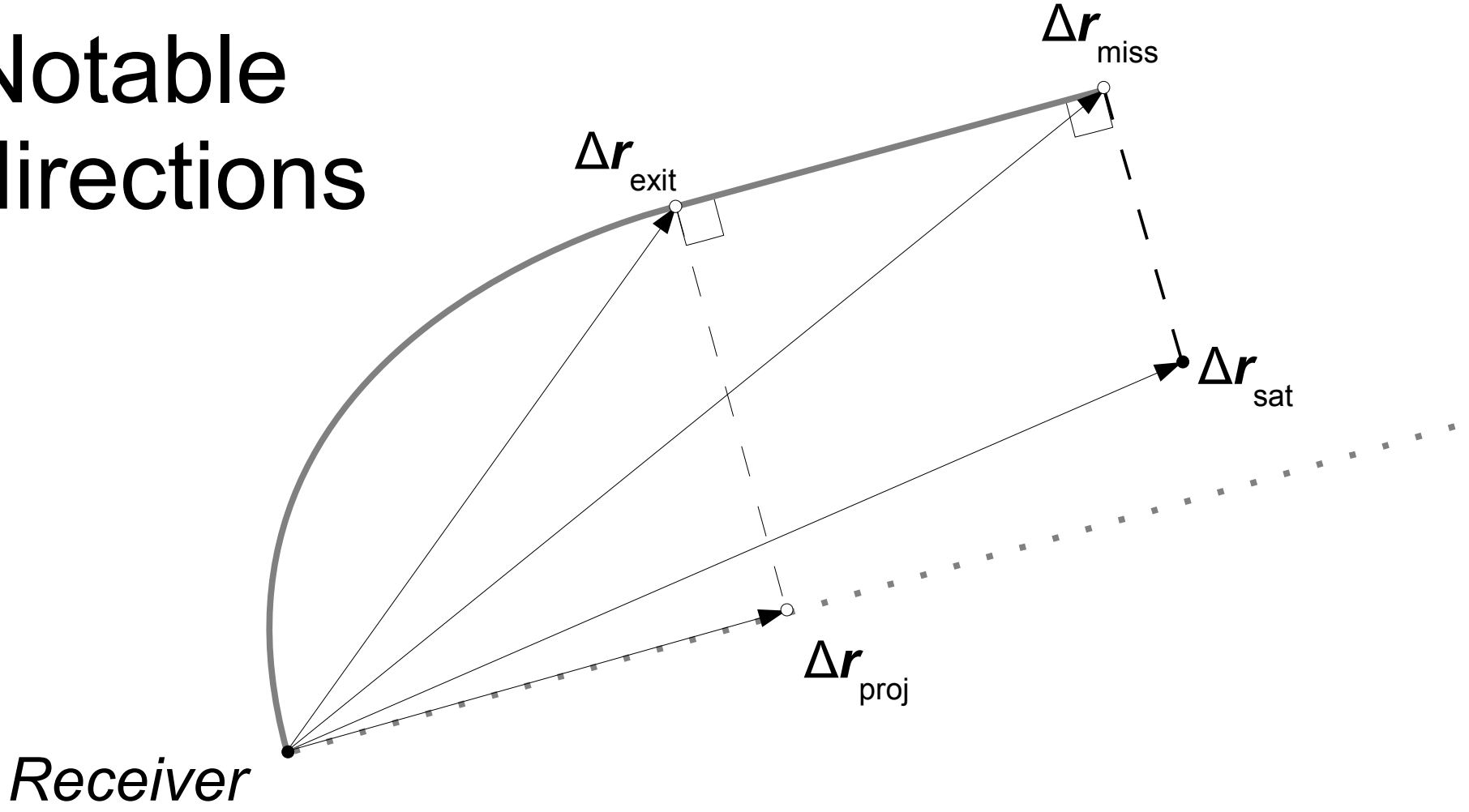
(Backup slides)

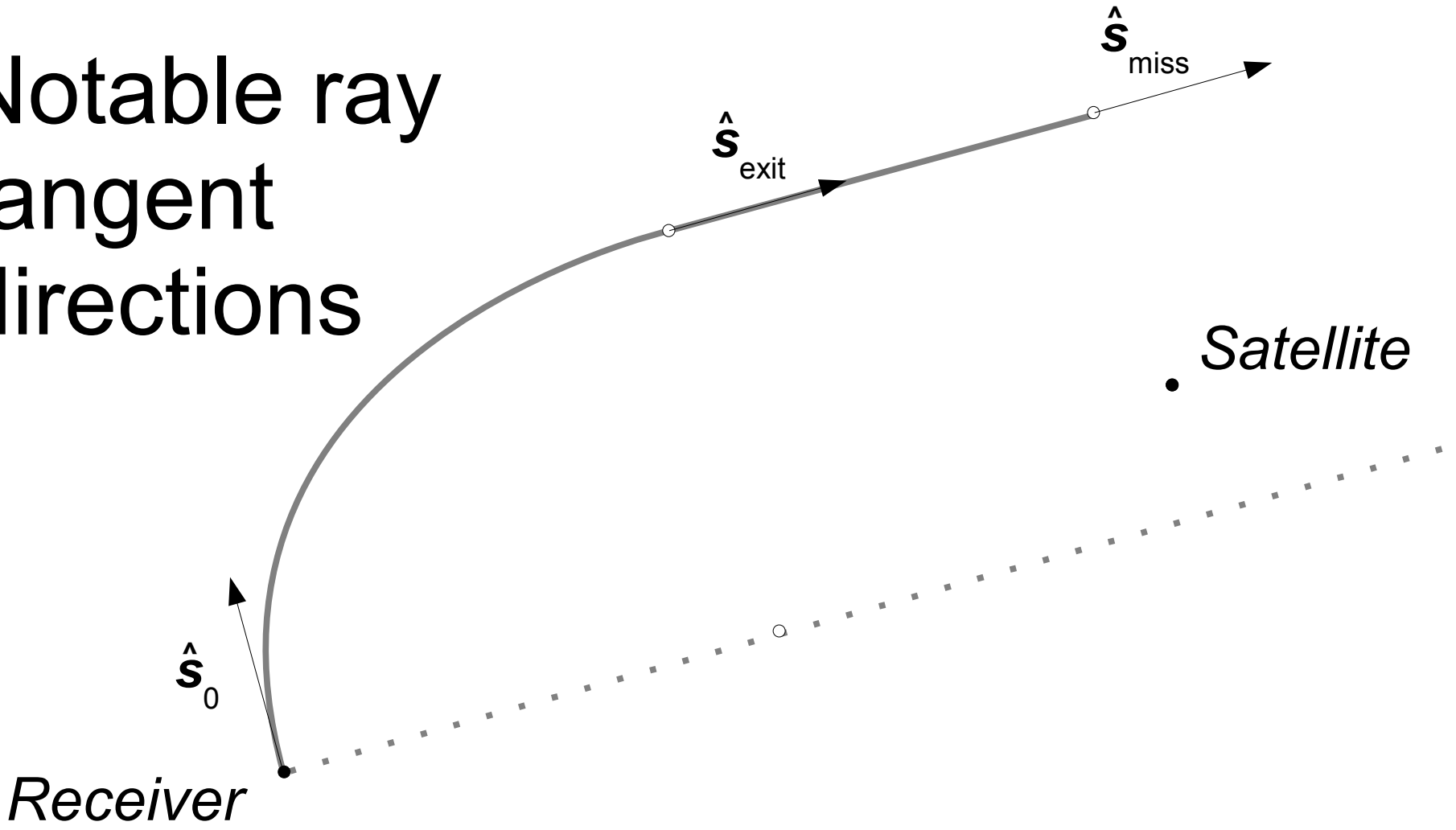
Notable points



Notable directions



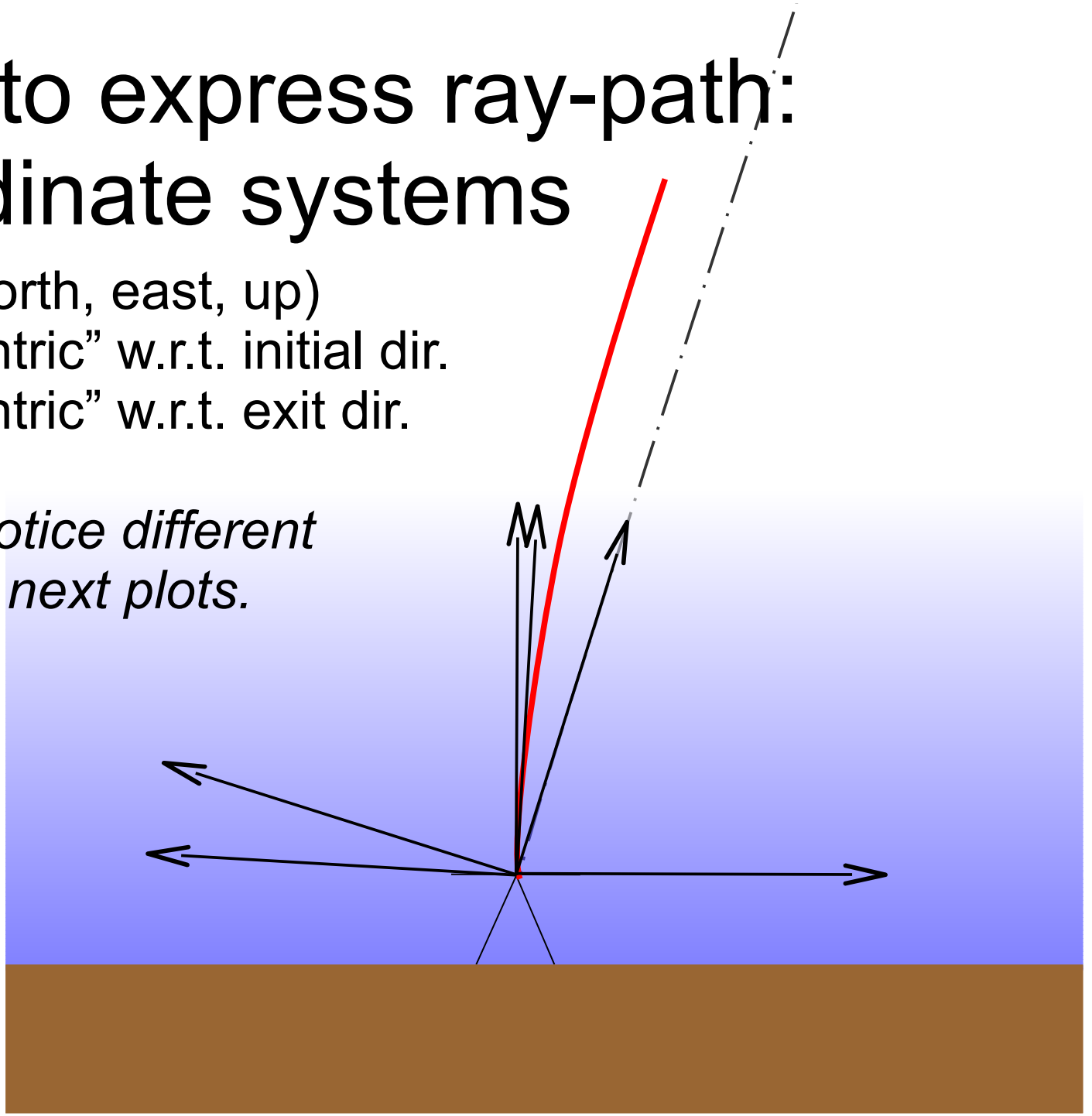
Notable ray tangent directions



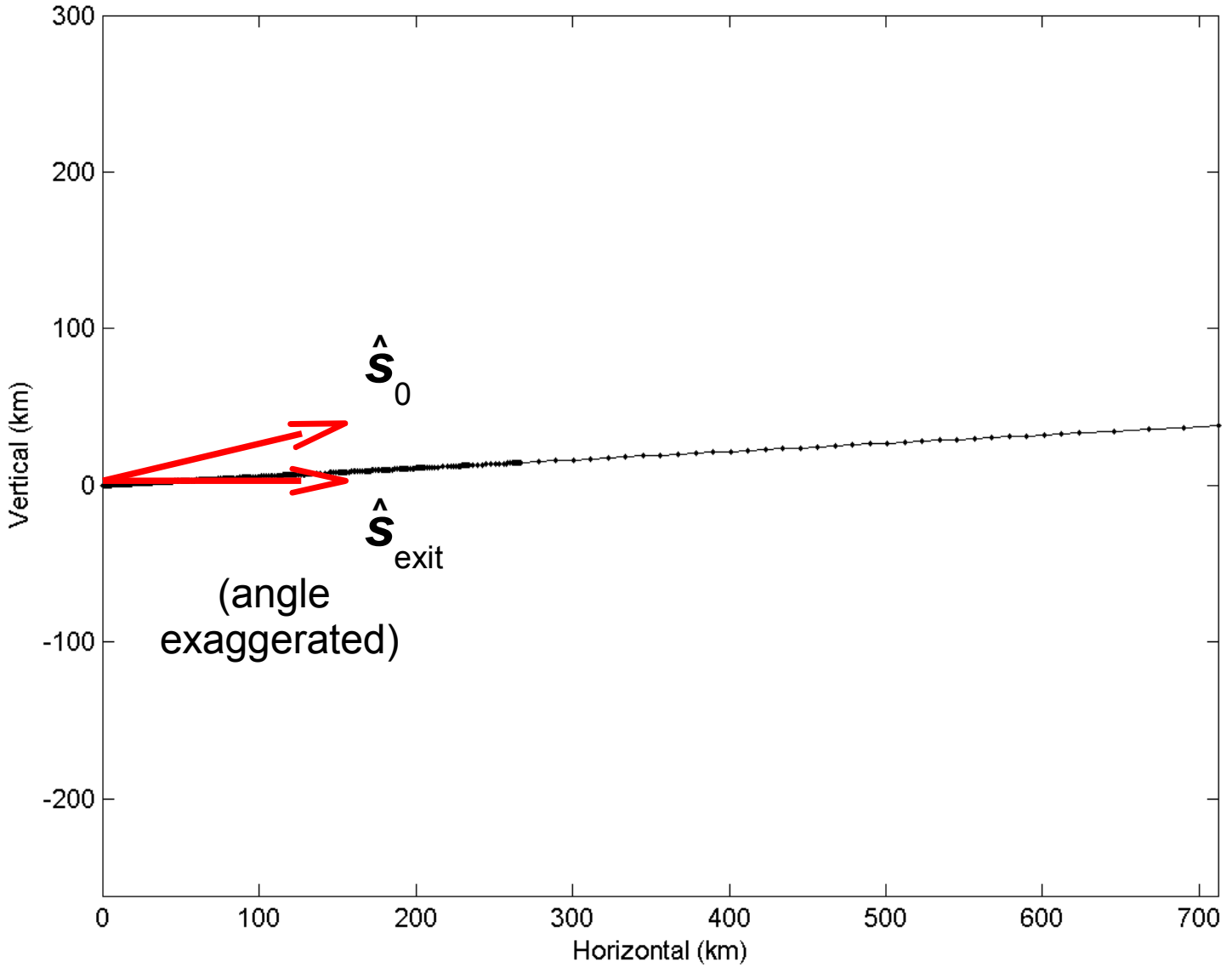
How to express ray-path: coordinate systems

- local (north, east, up)
- “ray-centric” w.r.t. initial dir.
- “ray-centric” w.r.t. exit dir.

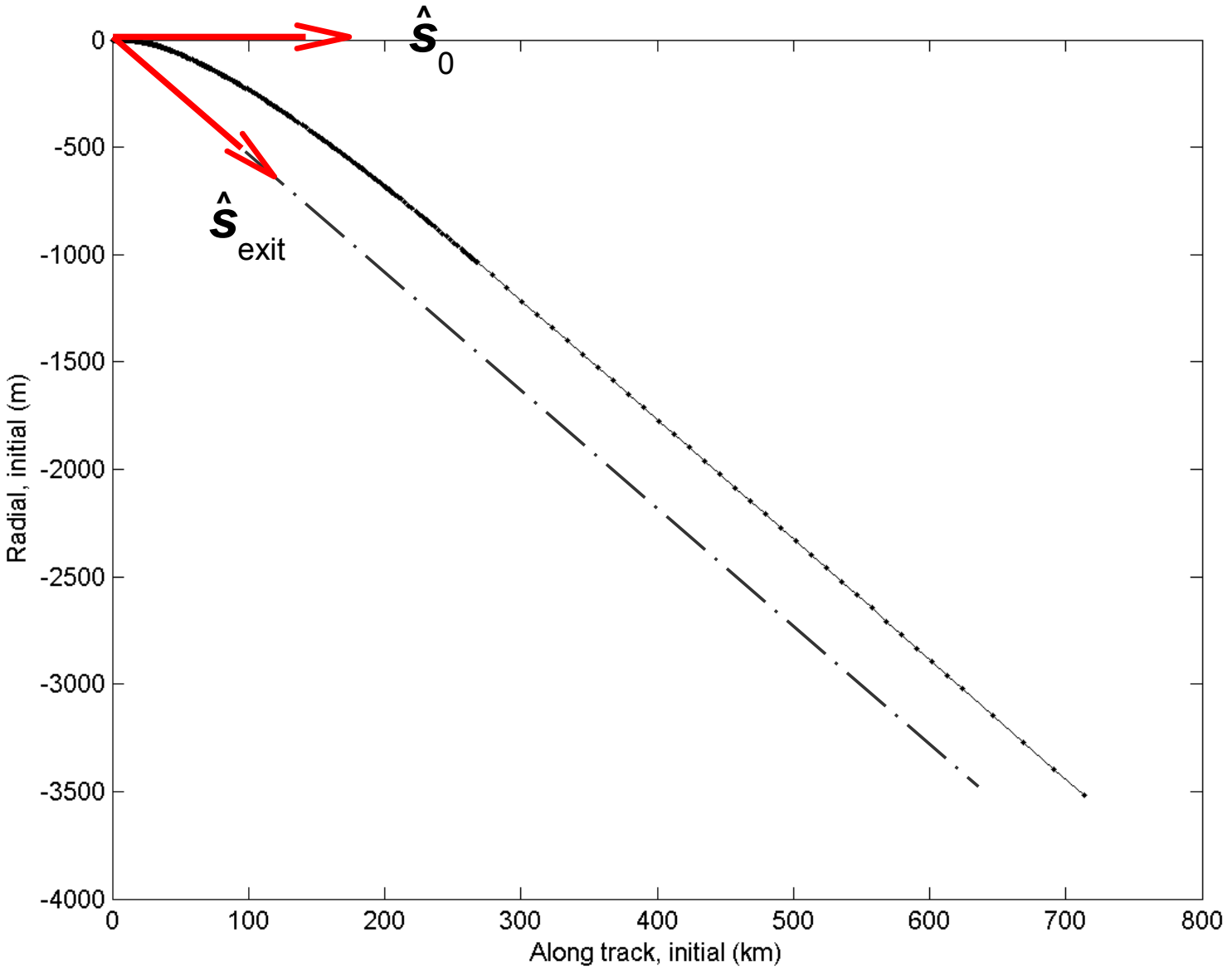
Please notice different scales in next plots.



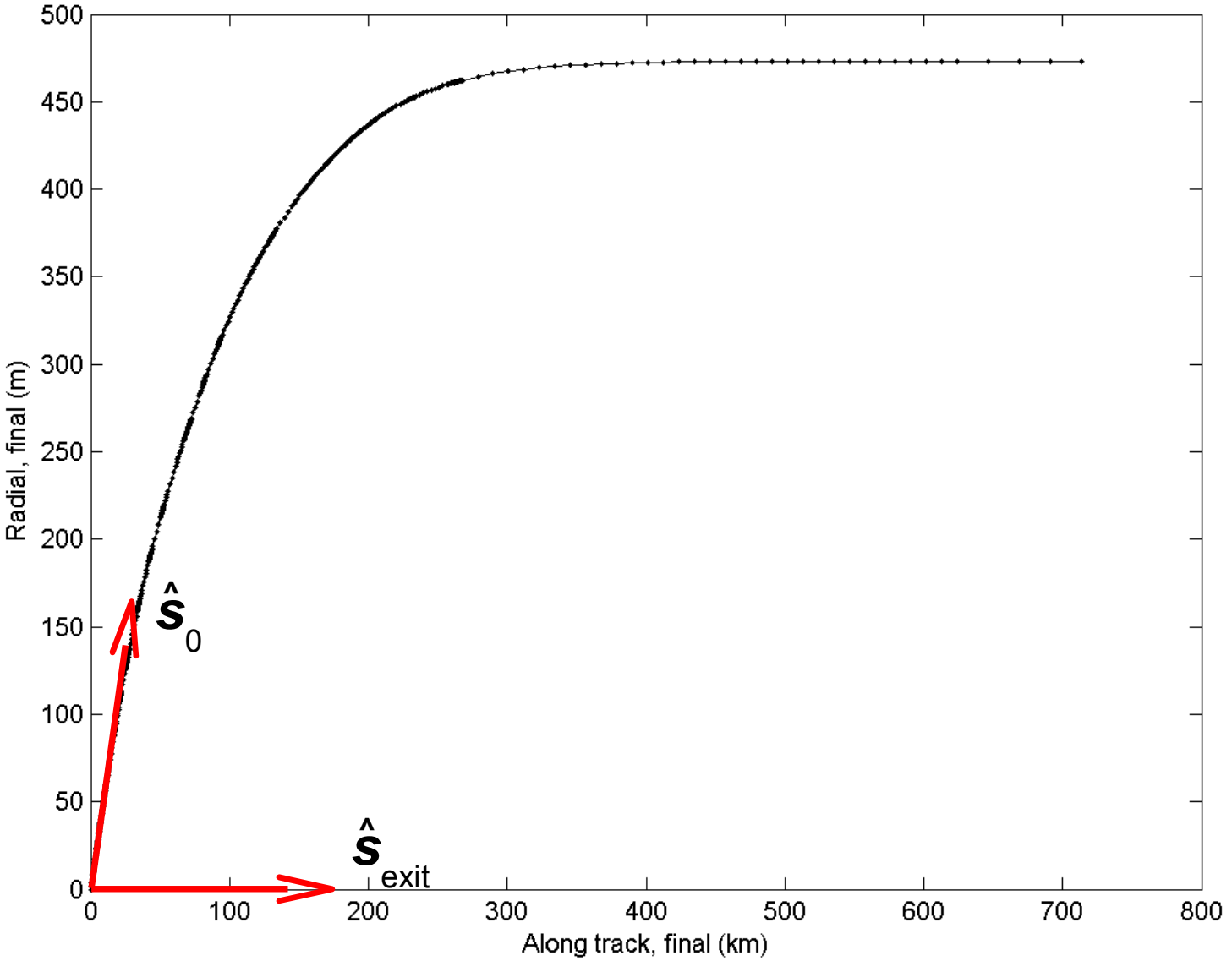
3º ray-path in local Cartesian sys.



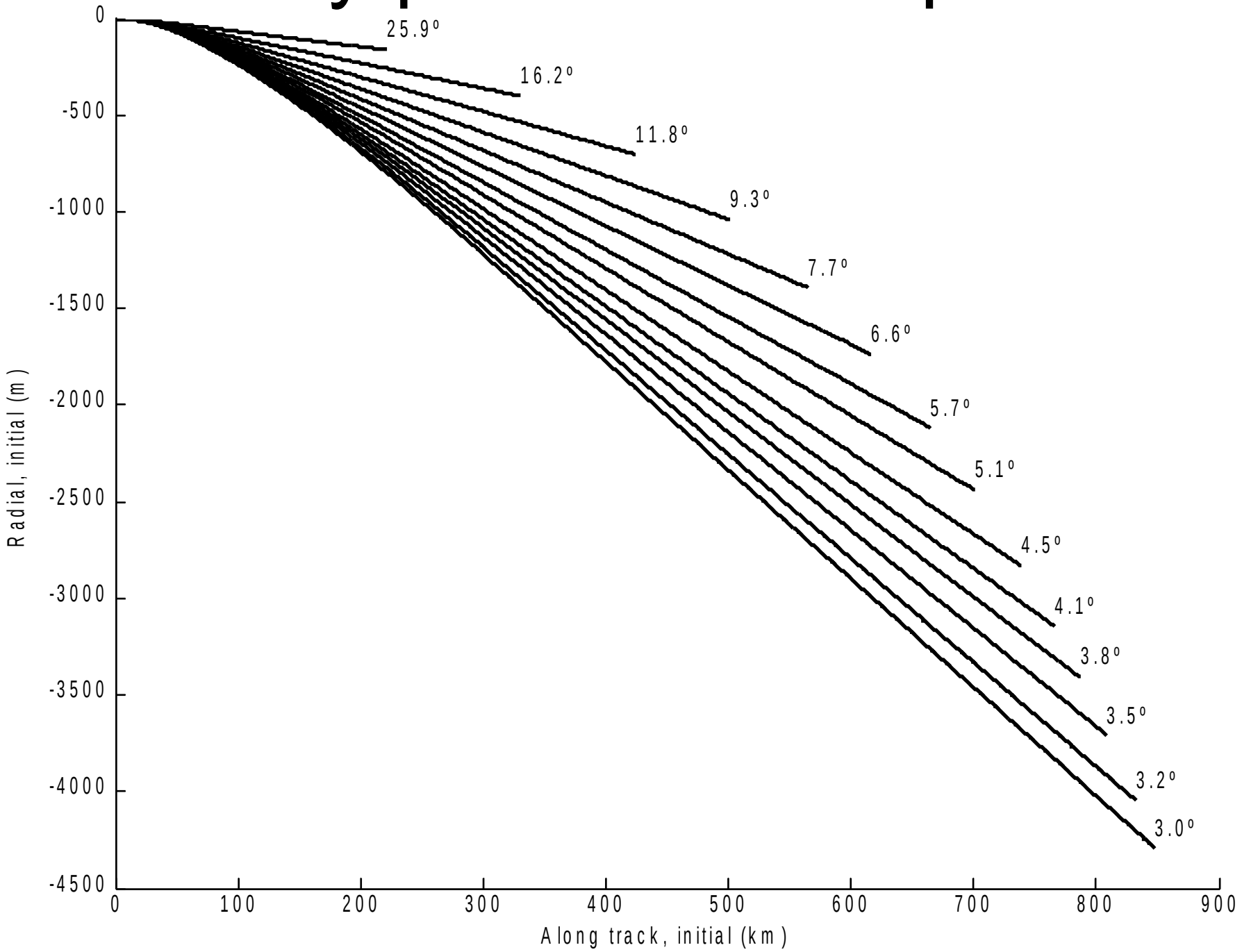
3º ray-path w.r.t. ray initial dir.



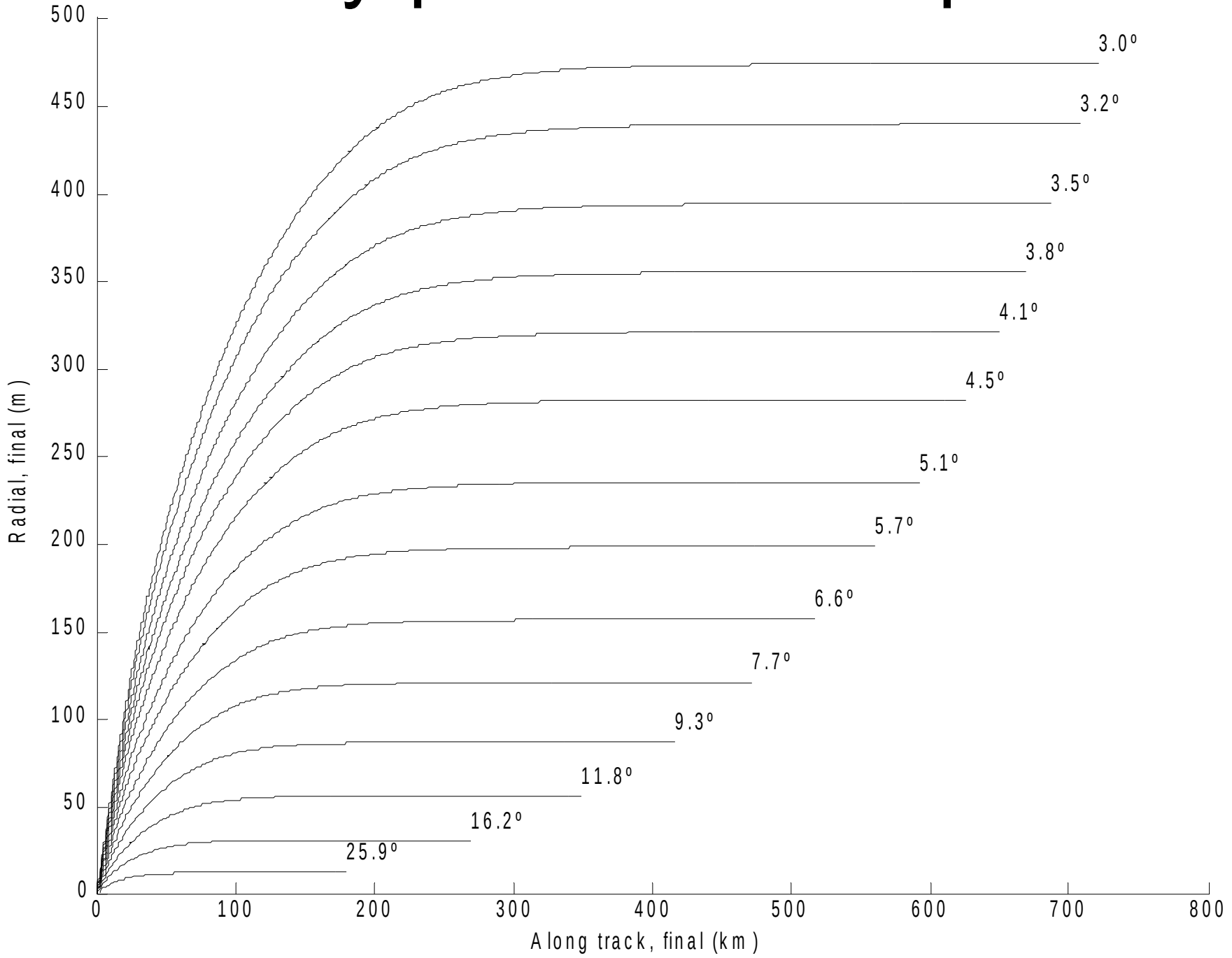
3º ray-path w.r.t. ray exit dir.



Several ray-paths w.r.t. resp. initial dir.



Several ray-paths w.r.t. resp. exit dir.



Modeling a priori ray-path