Find reflexion points on a a 3d surface

September 4, 2022

Contents

1 Notations

- $\underline{\mathrm{A}}$ is the point of observation
- $\underline{\mathrm{B}}$ is the point observed
- $\underline{\mathrm{C}}$ is the local coordinate center of the 3d surface
- $\underline{\mathrm{D}}$ is the projection of $\underline{\mathrm{B}}$ on the 3d surface as seen from $\underline{\mathrm{A}}$
- $\underline{\mathrm{e}}$ is the unit vector such that $\underline{\mathrm{AB}} = \| \underline{\mathrm{AB}} \| \, \underline{\mathrm{e}} = l \, \underline{\mathrm{e}}$
- $\underline{\mathrm{E}}$ is a point on (AB) parameterized by $\underline{AE} = kl \, \underline{\mathrm{e}}$
- $\underline{\mathrm{n}}(D)$ is the normal vector of the 3d surface at point $\underline{\mathrm{D}}$

Point $\underline{\mathrm{D}}$ on the 3d sufarce is the reflexion point connecting A and B. It means that $\underline{\mathrm{n}}(D)$ is in the same plane as (A, D, B).

Point $\underline{\mathrm{E}}$ on is the projection, on line (A, B) of point $\underline{\mathrm{D}}$ along $\underline{\mathrm{n}}$.

The idea is to look for $\underline{\mathrm{E}}$, which is parameterized by k, and then derive $\underline{\mathrm{D}}$ from $\underline{\mathrm{E}}$.

Hence both $\underline{\mathrm{n}}(\underline{\mathrm{D}})$ and $d_E = \| \underline{\mathrm{ED}} \|$ are parametrized by k: $\underline{\mathrm{n}}(k)$ and $d_E(k)$.

2 General equations

2.1 co-planarity

The point $\underline{\mathrm{D}}$ on the 3d sufarce is such that $\underline{\mathrm{n}}(D)$ is in the same plane as (A, D, B), which is written:

$$(\underline{\mathrm{DA}} \wedge \underline{\mathrm{n}}) \cdot (\underline{\mathrm{DB}} \wedge \underline{\mathrm{n}}) = 0 \tag{1}$$

$$\begin{aligned}
& (\underline{\mathrm{DA}} \wedge \underline{\mathrm{n}}) \wedge (\underline{\mathrm{DB}} \wedge \underline{\mathrm{n}}) = 0 \\
\Leftrightarrow\ & (\underline{\mathrm{EA}} \wedge \underline{\mathrm{n}}) \wedge (\underline{\mathrm{EB}} \wedge \underline{\mathrm{n}}) = 0 \\
& ((-kl)\, \underline{\mathrm{e}} \wedge \underline{\mathrm{n}}) \wedge ((1-k)le \wedge \underline{\mathrm{n}}) = 0 \\
& k(1-k)l^2 (\underline{\mathrm{e}} \wedge \underline{\mathrm{n}}) \wedge (\underline{\mathrm{e}} \wedge \underline{\mathrm{n}}) = 0
\end{aligned}$$

Which is true by construction of E.

2.2 equal angles

Since it is a specular reflexion, angles (A, D, E) and (B, D, E) are equal, which means $\underline{\mathrm{E}}$ is necessarily standing on the bisector of angle (A, D, B).

As such, the distance between $\underline{\mathrm{E}}$ and line (A, D) is equal to the distance between $\underline{\mathrm{E}}$ and line (B, D), which is written:

$$d_{E,(A,D)} = \frac{\| \underline{\mathrm{AD}} \wedge \underline{AE} \|}{\| \underline{\mathrm{AD}} \|} = \frac{\| \underline{\mathrm{BD}} \wedge \underline{BE} \|}{\| \underline{\mathrm{BD}} \|} = d_{E,(B,D)}$$

Knowing that:

$$\begin{aligned}
\| \underline{\mathrm{AD}} \|^2 &= \| \underline{AE} + \underline{\mathrm{ED}} \|^2 \\
&= k^2 l^2 + d_E^2 + 2 \underline{AE} \cdot \underline{\mathrm{ED}} \\
&= k^2 l^2 + d_E^2 + 2kl\, \underline{\mathrm{e}} \cdot (-d_E)\, \underline{\mathrm{n}} \\
&= k^2 l^2 + d_E(k)^2 - 2kl d_E(k)\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}}(k)
\end{aligned}$$

Similarly:

$$\begin{aligned}
\| \underline{\mathrm{BD}} \|^2 &= \| \underline{BE} + \underline{\mathrm{ED}} \|^2 \\
&= (1-k)^2 l^2 + d_E^2 + 2 \underline{BE} \cdot \underline{\mathrm{ED}} \\
&= (1-k)^2 l^2 + d_E^2 + 2(1-k)l(-\underline{\mathrm{e}}) \cdot (-d_E)\, \underline{\mathrm{n}} \\
&= (1-k)^2 l^2 + d_E(k)^2 + 2(1-k) l d_E(k)\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}}(k)
\end{aligned}$$

And the cross-products:

$$\begin{aligned}
\| \underline{\mathrm{AD}} \wedge \underline{AE} \|^2 &= \| \underline{\mathrm{ED}} \wedge \underline{AE} \|^2 \\
&= \| (-d_E)\, \underline{\mathrm{n}} \wedge kl\, \underline{\mathrm{e}} \|^2 \\
&= k^2 d_E(k)^2 l^2 \| \underline{\mathrm{n}}(k) \wedge \underline{\mathrm{e}} \|^2
\end{aligned}$$

And:

$$\begin{aligned}
\| \underline{\mathrm{BD}} \wedge \underline{BE} \|^2 &= \| \underline{\mathrm{ED}} \wedge \underline{BE} \|^2 \\
&= \| (-d_E)\, \underline{\mathrm{n}} \wedge (1-k)l(-\underline{\mathrm{e}}) \|^2 \\
&= (1-k)^2 d_E(k)^2 l^2 \| \underline{\mathrm{n}}(k) \wedge \underline{\mathrm{e}} \|^2
\end{aligned}$$

So in the end:

$$\begin{aligned}
& d_{E,(A,D)}^2 = d_{E,(B,D)}^2 \\
\Leftrightarrow\ & \| \underline{\mathrm{AD}} \wedge \underline{AE} \|^2 \| \underline{\mathrm{BD}} \|^2 = \| \underline{\mathrm{BD}} \wedge \underline{BE} \|^2 \| \underline{\mathrm{AD}} \|^2 \\
\Leftrightarrow\ & k^2 d_E^2 l^2 \| \underline{\mathrm{n}} \wedge \underline{\mathrm{e}} \|^2 \left[(1-k)^2 l^2 + d_E^2 + 2(1-k) l d_E\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} \right] \\
& = (1-k)^2 d_E^2 l^2 \| \underline{\mathrm{n}} \wedge \underline{\mathrm{e}} \|^2 \left[k^2 l^2 + d_E^2 - 2kl d_E\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} \right]
\end{aligned}$$

So assuming that:

$$\begin{cases} \| \underline{\mathrm{n}}(k) \wedge \underline{\mathrm{e}} \| \neq 0 \\ l \neq 0 \\ d_E(k) \neq 0 \end{cases}$$

So in the end:

$$\begin{aligned}
& d_{E,(A,D)}^2 = d_{E,(B,D)}^2 \\
\Leftrightarrow\ & k^2 \left[(1-k)^2 l^2 + d_E^2 + 2(1-k) l d_E\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} \right] = (1-k)^2 \left[k^2 l^2 + d_E^2 - 2kl d_E\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} \right] \\
\Leftrightarrow\ & k^2 \left[d_E^2 + 2(1-k) l d_E\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} \right] = (1-k)^2 \left[d_E^2 - 2kl d_E\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} \right] \\
\Leftrightarrow\ & k^2 d_E^2 + 2k^2(1-k) l d_E\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} = (1-k)^2 d_E^2 - 2(1-k)^2 kl d_E\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} \\
\Leftrightarrow\ & 2k d_E^2 - d_E^2 + 2k(1-k) l d_E\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} (k + 1 - k) = 0 \\
\Leftrightarrow\ & (2k-1) d_E + 2k(1-k) l\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}} = 0
\end{aligned}$$

Hence:

$$(2) \Leftrightarrow (2k-1) d_E(k) + 2k(1-k) l\, \underline{\mathrm{e}} \cdot \underline{\mathrm{n}}(k) = 0$$

2.3 equal angles 2

Deriving with a different method to double-check the formula. This time we use the scalar product:

$$(\underline{\mathrm{DA}}\cdot\underline{\mathrm{n}})^2\|DB\|^2 = (\underline{\mathrm{DB}}\cdot\underline{\mathrm{n}})^2\|DA\|^2$$

With:

$$\begin{cases} \underline{\mathrm{DA}}\cdot\underline{\mathrm{n}} = d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} \\ \underline{\mathrm{DB}}\cdot\underline{\mathrm{n}} = d + (1-k)l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} \\ \|\,\underline{\mathrm{DA}}\,\|^2 = d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} \\ \|\,\underline{\mathrm{DB}}\,\|^2 = d^2 + (1-k)^2l^2 + 2d(1-k)l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} \end{cases}$$

So:

$$\begin{array}{ll}
 & (\underline{\mathrm{DA}}\cdot\underline{\mathrm{n}})^2\|DB\|^2 = (\underline{\mathrm{DB}}\cdot\underline{\mathrm{n}})^2\|DA\|^2 \\
\Leftrightarrow & (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})^2(d^2 + (1-k)^2l^2 + 2d(1-k)l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) = (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})^2(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})^2((1-k)^2l^2 + 2d(1-k)l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} - k^2l^2 + 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) = (l^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2 + 2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}))(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})^2(l^2 - 2kl^2 + 2dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) = l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + 2(d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}))(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})\left[(d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})(l^2 - 2kl^2 + 2dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) - 2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})\right] = l^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})\left[(d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})(l^2 - 2kl^2 + 2dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) - 2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})\right] = l^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})\left[d(l^2 - 2kl^2) - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(l^2 - 2kl^2 + 2dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) - 2k^2l^3\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + 4dkl^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2\right] = l^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})\left[d(l^2 - 2kl^2) - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(l^2 + 2dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) + 4dkl^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2\right] = l^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})\left[d(l^2 - 2kl^2) - kl^3\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + 2dkl^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2\right] = l^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & (d - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})\left[d(1 - 2k) - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + 2dk\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2\right] = \underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & d^2(1-2k) - kdl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + 2d^2k\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2 - kdl(1-2k)\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + k^2l^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2 - 2dk^2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^3 = \underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2(d^2 + k^2l^2 - 2dkl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) \\
\Leftrightarrow & k^2(2dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + l^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2 - 2dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^3 - l^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2) + k(-2d^2 - dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + 2d^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2 - dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + 2dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^3) + d^2 - d^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2 = 0 \\
\Leftrightarrow & k^2 2dl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(1 - \underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2) + k2d(-d - l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + d\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2 + l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^3) + d^2(1 - \underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2) = 0 \\
\Leftrightarrow & k^2 2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(1 - \underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2) - k2(d - d\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2 + l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} - l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^3) + d(1 - \underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2) = 0 \\
\Leftrightarrow & k^2 2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(1 - \underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2) - k2(d + l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}})(1 - \underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2) + d(1 - \underline{\mathrm{e}}\cdot\underline{\mathrm{n}}^2) = 0 \\
\Leftrightarrow & k^2 2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} - k2(d + l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) + d = 0 \\
\Leftrightarrow & d(1-2k) + 2lk^2\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} - 2kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} = 0 \\
\Leftrightarrow & (2k-1)d_E(k) + 2k(1-k)l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(k) = 0
\end{array}$$

3 Planar

If the 3d surface is a plane, then $\underline{\mathrm{n}}$ is constant and does not depend on k.

The equations become:

$$(2k-1)d_E(k) + 2k(1-k)l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} = 0 \tag{2}$$

In that case:

$$\begin{aligned} d_E(k) &= \underline{\mathrm{DE}}\cdot\underline{\mathrm{n}} \\ &= (\underline{\mathrm{DC}} + \underline{\mathrm{CA}} + \underline{AE})\cdot\underline{\mathrm{n}} \\ &= \underline{\mathrm{CA}}\cdot\underline{\mathrm{n}} + kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} \end{aligned}$$

Which means:

$$\begin{aligned} (2) \quad &\Leftrightarrow 2k(\underline{\mathrm{CA}}\cdot\underline{\mathrm{n}} + kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) - \underline{\mathrm{CA}}\cdot\underline{\mathrm{n}} - kl\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + 2k(1-k)l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} = 0 \\ &\Leftrightarrow k^2(2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} - 2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) + k(2\,\underline{\mathrm{CA}}\cdot\underline{\mathrm{n}} - l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} + 2l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) - \underline{\mathrm{CA}}\cdot\underline{\mathrm{n}} = 0 \\ &\Leftrightarrow k(2\,\underline{\mathrm{CA}}\cdot\underline{\mathrm{n}} + l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}) - \underline{\mathrm{CA}}\cdot\underline{\mathrm{n}} = 0 \end{aligned}$$

So finally:

$$(2) \Leftrightarrow k = \frac{\underline{\mathrm{CA}}\cdot\underline{\mathrm{n}}}{2\,\underline{\mathrm{CA}}\cdot\underline{\mathrm{n}} + l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}}$$

4 Cylinder

Consider a cylinder of axes $(O, \underline{z})$, with $\underline{z}$ unit vector and radius r. The normal vector associated to any point E (not on the axis) is:

$$\underline{n}(E) = -\frac{(\underline{OE} \wedge \underline{z}) \wedge \underline{z}}{\|(\underline{OE} \wedge \underline{z}) \wedge \underline{z}\|} = -\frac{(\underline{OE} \wedge \underline{z}) \wedge \underline{z}}{\|\underline{\mathrm{OE}} \wedge \underline{z}\|}$$

Given that E in on the (A, B) line:

$$\underline{OE} = \underline{OA} + kl\,\underline{e}$$

So:

$$(\underline{OE} \wedge \underline{z}) \wedge \underline{z} = (\underline{OA} \wedge \underline{z}) \wedge \underline{z} + kl(\underline{e} \wedge \underline{z}) \wedge \underline{z}$$

Which entails:

$$\begin{aligned} \underline{e} \cdot \underline{n}(k) &= -\tfrac{1}{\|\underline{\mathrm{OE}} \wedge \underline{z}\|}\left[\underline{e} \cdot ((\underline{OE} \wedge \underline{z}) \wedge \underline{z})\right] \\ &= \tfrac{1}{\|\underline{\mathrm{OE}} \wedge \underline{z}\|}\left[(\underline{OE} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z})\right] \end{aligned}$$

And:

$$d_E = r - \|\underline{\mathrm{OE}} \wedge \underline{z}\|$$

So the equation becomes:

$$\begin{aligned} (2) \quad &\Leftrightarrow (2k-1)(r - \|\underline{\mathrm{OE}} \wedge \underline{z}\|) + 2k(1-k)l\,\underline{e} \cdot \underline{n} = 0 \\ &\Leftrightarrow (2k-1)(r - \|\underline{\mathrm{OE}} \wedge \underline{z}\|)\,\|\underline{\mathrm{OE}} \wedge \underline{z}\| + 2k(1-k)l\left[(\underline{OE} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z}))\right] = 0 \\ &\Leftrightarrow (2k-1)r\,\|\underline{\mathrm{OE}} \wedge \underline{z}\| - (2k-1)\,\|\underline{\mathrm{OE}} \wedge \underline{z}\|^2 + 2k(1-k)l\left[(\underline{OE} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z})\right] = 0 \end{aligned}$$

Observing that:

$$\underline{OE} \wedge \underline{z} = \underline{\mathrm{OA}} \wedge \underline{z} + kl\,\underline{e} \wedge \underline{z}$$

And:

$$\|\underline{\mathrm{OE}} \wedge \underline{z}\|^2 = \|\,\underline{\mathrm{OA}} \wedge \underline{z} + kl\,\underline{e} \wedge \underline{z}\,\|^2 = (\underline{\mathrm{OA}} \wedge \underline{z})^2 + 2kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z}) + k^2l^2(\underline{e} \wedge \underline{z})^2$$

So

$$\begin{aligned} (2) \quad \Leftrightarrow \quad & (2k-1)r\,\|\underline{\mathrm{OE}} \wedge \underline{z}\| - (2k-1)(\underline{\mathrm{OA}} \wedge \underline{z})^2 - (2k-1)2kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z}) - (2k-1)k^2l^2(\underline{e} \wedge \underline{z})^2 \\ & + 2k(1-k)l(\underline{OA} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z}) + 2k^2(1-k)l^2(\underline{e} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z}) = 0 \\ \Leftrightarrow \quad & (2k-1)r\,\|\underline{\mathrm{OE}} \wedge \underline{z}\| - (2k-1)(\underline{\mathrm{OA}} \wedge \underline{z})^2 + 2kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z})(1-k-2k+1) + k^2l^2(\underline{e} \wedge \underline{z})^2(2-2k-2k+1) = 0 \\ \Leftrightarrow \quad & (2k-1)r\,\|\underline{\mathrm{OE}} \wedge \underline{z}\| - (2k-1)(\underline{\mathrm{OA}} \wedge \underline{z})^2 + 2kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z})(2-3k) + k^2l^2(\underline{e} \wedge \underline{z})^2(3-4k) = 0 \\ \Leftrightarrow \quad & (2k-1)r\,\|\underline{\mathrm{OE}} \wedge \underline{z}\| = (2k-1)(\underline{\mathrm{OA}} \wedge \underline{z})^2 - 2kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z})(2-3k) - k^2l^2(\underline{e} \wedge \underline{z})^2(3-4k) \\ \Leftrightarrow \quad & (2k-1)^2r^2(\underline{\mathrm{OA}} \wedge \underline{z})^2 + (2k-1)^2r^22kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z}) + (2k-1)^2r^2k^2l^2(\underline{e} \wedge \underline{z})^2 \\ & = \left[(2k-1)(\underline{\mathrm{OA}} \wedge \underline{z})^2 - 2kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z})(2-3k) - k^2l^2(\underline{e} \wedge \underline{z})^2(3-4k)\right]^2 \\ \Leftrightarrow \quad & (2k-1)^2r^2(\underline{\mathrm{OA}} \wedge \underline{z})^2 + (2k-1)^2r^22kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z}) + (2k-1)^2r^2k^2l^2(\underline{e} \wedge \underline{z})^2 \\ & = (2k-1)^2(\underline{\mathrm{OA}} \wedge \underline{z})^4 - 2(2k-1)(\underline{\mathrm{OA}} \wedge \underline{z})^22kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z})(2-3k) - 2(2k-1)(\underline{\mathrm{OA}} \wedge \underline{z})^2k^2l^2(\underline{e} \wedge \underline{z})^2(3-4k) \\ & + 4k^2l^2\left((\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z})\right)^2(2-3k)^2 + k^4l^4(\underline{e} \wedge \underline{z})^4(3-4k)^2 + 4kl(\underline{\mathrm{OA}} \wedge \underline{z}) \cdot (\underline{e} \wedge \underline{z})(2-3k)k^2l^2(\underline{e} \wedge \underline{z})^2(3-4k) \\ \Leftrightarrow \quad & (2k-1)^2A + k(2k-1)^2B + k^2(2k-1)^2C \\ & = -k(2k-1)(2-3k)D - k^2(2k-1)(3-4k)E + k^2(2-3k)^2F + k^4(3-4k)^2G + k^3(2-3k)(3-4k)H \\ \Leftrightarrow \quad & k^6(16G) \\ & + k^5(-12H + 24G) \\ & + k^4(8H + 9H - 9G - 9F - 8E + 4C) \\ & + k^3(-6H + 12F + 6E + 4E - 6D - 4C + 4B) \\ & + k^2(-4F - 3E + 4D + 3D + C - 4B + 4A) \\ & + k(-2D + B - 4A) \\ & + A = 0 \\ \Leftrightarrow \quad & k^6(16G) \\ & + k^5(-12H + 24G) \\ & + k^4(17H - 9G - 9F - 8E + 4C) \\ & + k^3(-6H + 12F + 10E - 6D - 4C + 4B) \\ & + k^2(-4F - 3E + 7D + C - 4B + 4A) \\ & + k(-2D + B - 4A) \\ & + A = 0 \end{aligned}$$

Where:

$$\begin{cases} A = (r^2 - (\underline{\mathrm{OA}} \wedge \underline{\mathrm{z}})^2)(\underline{\mathrm{OA}} \wedge \underline{\mathrm{z}})^2 \\ B = 2r^2 l(\underline{\mathrm{OA}} \wedge \underline{\mathrm{z}}) \cdot (\underline{\mathrm{e}} \wedge \underline{\mathrm{z}}) \\ C = r^2 l^2 (\underline{\mathrm{e}} \wedge \underline{\mathrm{z}})^2 \\ D = 4l(\underline{\mathrm{OA}} \wedge \underline{\mathrm{z}})^2 (\underline{\mathrm{OA}} \wedge \underline{\mathrm{z}}) \cdot (\underline{\mathrm{e}} \wedge \underline{\mathrm{z}}) \\ E = 2l^2 (\underline{\mathrm{OA}} \wedge \underline{\mathrm{z}})^2 (\underline{\mathrm{e}} \wedge \underline{\mathrm{z}})^2 \\ F = 4l^2 \left((\underline{\mathrm{OA}} \wedge \underline{\mathrm{z}}) \cdot (\underline{\mathrm{e}} \wedge \underline{\mathrm{z}})\right)^2 \\ G = l^4 (\underline{\mathrm{e}} \wedge \underline{\mathrm{z}})^4 \\ H = 4l^3 (\underline{\mathrm{OA}} \wedge \underline{\mathrm{z}}) \cdot (\underline{\mathrm{e}} \wedge \underline{\mathrm{z}})(\underline{\mathrm{e}} \wedge \underline{\mathrm{z}})^2 \end{cases}$$

5 Sphere

Consider a sphere of center O and radius r. The normal vector associated to any point E (not on O) is:

$$\underline{\mathrm{n}}(E) = -\frac{\underline{OE}}{\|\underline{\mathrm{OE}}\|}$$

Given that E in on the (A, B) line:

$$\begin{cases} \underline{OE} = \underline{\mathrm{OA}} + kl\,\underline{\mathrm{e}} \\ \|\underline{OE}\|^2 = \|\,\underline{\mathrm{OA}}\,\|^2 + k^2l^2 + 2kl\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} \end{cases}$$

Which entails:

$$\underline{\mathrm{e}}\cdot\underline{\mathrm{n}}(k) \quad = -\tfrac{1}{\|\underline{\mathrm{OE}}\|}\left[\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} + kl\right]$$

And:

$$d_E = r - \|\underline{OE}\|$$

So the equation becomes:

$$\begin{array}{lll}
(2) & \Leftrightarrow & (2k-1)(r - \|\underline{\mathrm{OE}}\|) + 2k(1-k)l\,\underline{\mathrm{e}}\cdot\underline{\mathrm{n}} = 0 \\
& \Leftrightarrow & (2k-1)(r - \|\underline{\mathrm{OE}}\|)\,\|\underline{\mathrm{OE}}\| - 2k(1-k)l\left[\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} + kl\right] = 0 \\
& \Leftrightarrow & (2k-1)r\,\|\underline{\mathrm{OE}}\| - (2k-1)\,\|\underline{\mathrm{OE}}\|^2 - 2k(1-k)l\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} - 2k^2l^2(1-k) = 0 \\
& \Leftrightarrow & (2k-1)r\,\|\underline{\mathrm{OE}}\| - (2k-1)\|\,\underline{\mathrm{OA}}\,\|^2 - (2k-1)k^2l^2 - 2(2k-1)kl\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} - 2k(1-k)l\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} - 2k^2l^2(1-k) = 0 \\
& \Leftrightarrow & (2k-1)r\,\|\underline{\mathrm{OE}}\| - (2k-1)\|\,\underline{\mathrm{OA}}\,\|^2 - k^2l^2(2k-1+2-2k) - 2kl\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}}(2k-1+1-k) = 0 \\
& \Leftrightarrow & (2k-1)r\,\|\underline{\mathrm{OE}}\| - (2k-1)\|\,\underline{\mathrm{OA}}\,\|^2 - k^2l^2 - 2k^2l\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} = 0 \\
& \Leftrightarrow & (2k-1)^2r^2\,\|\underline{\mathrm{OE}}\|^2 = \left[(2k-1)\|\,\underline{\mathrm{OA}}\,\|^2 + k^2\left(\mathrm{l}^2 + 2\mathrm{l}\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}}\right)\right]^2 \\
& \Leftrightarrow & (2k-1)^2r^2\|\,\underline{\mathrm{OA}}\,\|^2 + (2k-1)^2r^2k^2l^2 + (2k-1)^2r^2 2kl\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} \\
& & = (2k-1)^2\|\,\underline{\mathrm{OA}}\,\|^4 + 2(2k-1)\|\,\underline{\mathrm{OA}}\,\|^2k^2\left(\mathrm{l}^2 + 2\mathrm{l}\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}}\right) + k^4\left(\mathrm{l}^2 + 2\mathrm{l}\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}}\right)^2 \\
& \Leftrightarrow & (2k-1)^2(r^2 - \|\,\underline{\mathrm{OA}}\,\|^2)\|\,\underline{\mathrm{OA}}\,\|^2 + (2k-1)^2r^2k^2l^2 + (2k-1)^2r^2 2kl\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} \\
& & = 2(2k-1)l\|\,\underline{\mathrm{OA}}\,\|^2k^2(l + 2\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}}) + k^4l^2(l + 2\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}})^2 \\
& \Leftrightarrow & (4k^2-4k+1)C_0 + (4k^2-4k+1)k^2C_1 + (4k^2-4k+1)kC_2 = (2k-1)k^2C_3 + k^4C_4 \\
& \Leftrightarrow & k^4\left[4C_1 - C_4\right] + k^3\left[-4C_1 + 4C_2 - 2C_3\right] + k^2\left[4C_0 + C_1 - 4C_2 + C_3\right] + k\left[-4C_0 + C_2\right] + C_0 = 0
\end{array}$$

Where:

$$\begin{cases} C_0 = (r^2 - \|\,\underline{\mathrm{OA}}\,\|^2)\|\,\underline{\mathrm{OA}}\,\|^2 \\ C_1 = r^2l^2 \\ C_2 = 2lr^2\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}} \\ C_3 = 2l\|\,\underline{\mathrm{OA}}\,\|^2(l + 2\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}}) \\ C_4 = l^2(l + 2\,\underline{\mathrm{OA}}\cdot\underline{\mathrm{e}})^2 \end{cases}$$

6 Torus

Consider a torus of axes $(O, \underline{z})$, with $\underline{z}$ unit vector. It has major radius $\mathrm{r_a}$ and minor radius $\mathrm{r_b}$.

For any point E in space, we have:

$$\underline{\mathrm{e}}_{\mathrm{a}}(E) = -\frac{(\underline{OE} \wedge \underline{z}) \wedge \underline{z}}{\|(\underline{OE} \wedge \underline{z}) \wedge \underline{z}\,\|} = -\frac{(\underline{OE} \wedge \underline{z}) \wedge \underline{z}}{\|\underline{\mathrm{OE}} \wedge \underline{z}\,\|}$$

Hence, the normal vector associated to any point E is:

$$\underline{\mathrm{n}}(E) = -\frac{\underline{OE} - \mathrm{r_a}\,\underline{\mathrm{e}}_{\mathrm{a}}}{\|\underline{OE} - \mathrm{r_a}\,\underline{\mathrm{e}}_{\mathrm{a}}\,\|}$$

Given that E in on the (A, B) line:

$$\underline{OE} = \underline{OA} + kl\,\underline{\mathrm{e}}$$

So:

$$(\underline{OE} \wedge \underline{z}) \wedge \underline{z} = (\underline{OA} \wedge \underline{z}) \wedge \underline{z} + kl(\underline{\mathrm{e}} \wedge \underline{z}) \wedge \underline{z}$$

Which entails:

$$\begin{aligned} \underline{\mathrm{e}} \cdot \underline{\mathrm{n}}(k) &= -\tfrac{1}{\|\underline{\mathrm{OE}} \wedge \mathrm{r_a}\,\underline{\mathrm{e}}_{\mathrm{a}}\,\|}\left[\underline{\mathrm{e}} \cdot \underline{OE} - \mathrm{r_a}\,\underline{\mathrm{e}} \cdot \underline{\mathrm{e}}_{\mathrm{a}})\right] \\ &= -\tfrac{1}{\|\underline{\mathrm{OE}} \wedge \mathrm{r_a}\,\underline{\mathrm{e}}_{\mathrm{a}}\,\|}\left[\underline{\mathrm{e}} \cdot \underline{\mathrm{OA}} + kl - \mathrm{r_a}\,\underline{\mathrm{e}} \cdot \underline{\mathrm{e}}_{\mathrm{a}})\right] \\ &= -\tfrac{1}{\|\underline{\mathrm{OE}} \wedge \mathrm{r_a}\,\underline{\mathrm{e}}_{\mathrm{a}}\,\|}\left[\underline{\mathrm{e}} \cdot \underline{\mathrm{OA}} + kl + \tfrac{\mathrm{r_a}}{\|\underline{\mathrm{OE}} \wedge \underline{z}\,\|}\,\underline{\mathrm{e}} \cdot ((\underline{OE} \wedge \underline{z}) \wedge \underline{z}))\right] \end{aligned}$$

And:

$$d_E = \mathrm{r_b} - \|\underline{OE} - \mathrm{r_a}\,\underline{\mathrm{e}}_{\mathrm{a}}\,\|$$

Where:

$$\begin{aligned} \|\underline{OE} - \mathrm{r_a}\,\underline{\mathrm{e}}_{\mathrm{a}}\,\|^2 &= \|\underline{\mathrm{OE}}\|^2 + \mathrm{r_a}^2 - 2\,\mathrm{r_a}\,\underline{OE} \cdot \underline{\mathrm{e}}_{\mathrm{a}} \\ &= \|\,\underline{\mathrm{OA}}\,\|^2 + k^2l^2 + 2kl\,\underline{\mathrm{OA}} \cdot \underline{\mathrm{e}} + \mathrm{r_a}^2 - 2\,\mathrm{r_a}\,\underline{OE} \cdot \underline{\mathrm{e}}_{\mathrm{a}} \\ &= \|\,\underline{\mathrm{OA}}\,\|^2 + k^2l^2 + 2kl\,\underline{\mathrm{OA}} \cdot \underline{\mathrm{e}} + \mathrm{r_a}^2 - 2\,\mathrm{r_a}\,\underline{OA} \cdot \underline{\mathrm{e}}_{\mathrm{a}} - 2kl\,\mathrm{r_a}\,\underline{\mathrm{e}} \cdot \underline{\mathrm{e}}_{\mathrm{a}} \end{aligned}$$