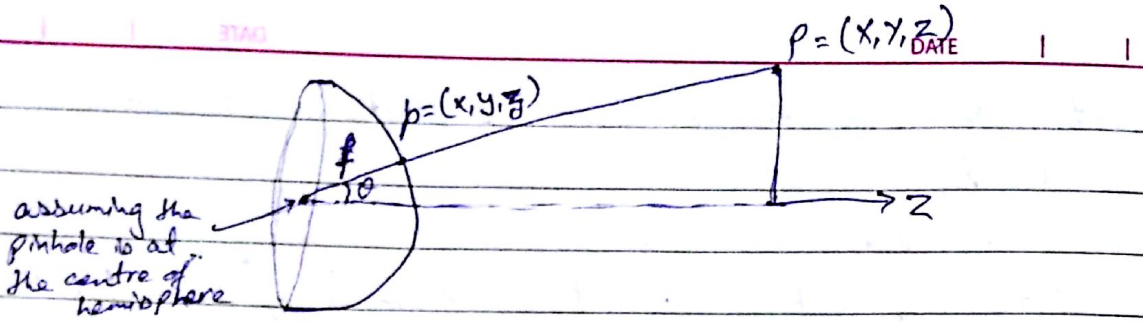
3.



$$x = -\frac{X f \cos\theta}{Z} \qquad y = -\frac{Y f \cos\theta}{Z} \qquad z = -\frac{Z f \cos\theta}{Z}$$

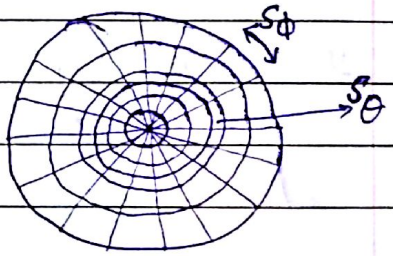
and $\cos\theta = \frac{Z}{\sqrt{X^2+Y^2+Z^2}}$

$$\therefore x = \frac{-f X}{\sqrt{X^2+Y^2+Z^2}} \qquad y = \frac{-f Y}{\sqrt{X^2+Y^2+Z^2}} \qquad z = \frac{-f Z}{\sqrt{X^2+Y^2+Z^2}}$$

$$\therefore \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{1}{\sqrt{X^2+Y^2+Z^2}} \begin{bmatrix} -f & 0 & 0 \\ 0 & -f & 0 \\ 0 & 0 & -f \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\Rightarrow \boxed{p = \frac{-f}{\|P\|} P}$$

where, both are in camera coordinate system.



So we need $O_\phi, O_\theta, S_\theta, S_\phi$ and f as the intrinsic parameter.

where, S_θ is divisions in θ

S_ϕ is divisions in ϕ

and f is the radius of hemisphere

O_θ is the θ-coordinate of optical centre

O_ϕ is the ϕ- " " "