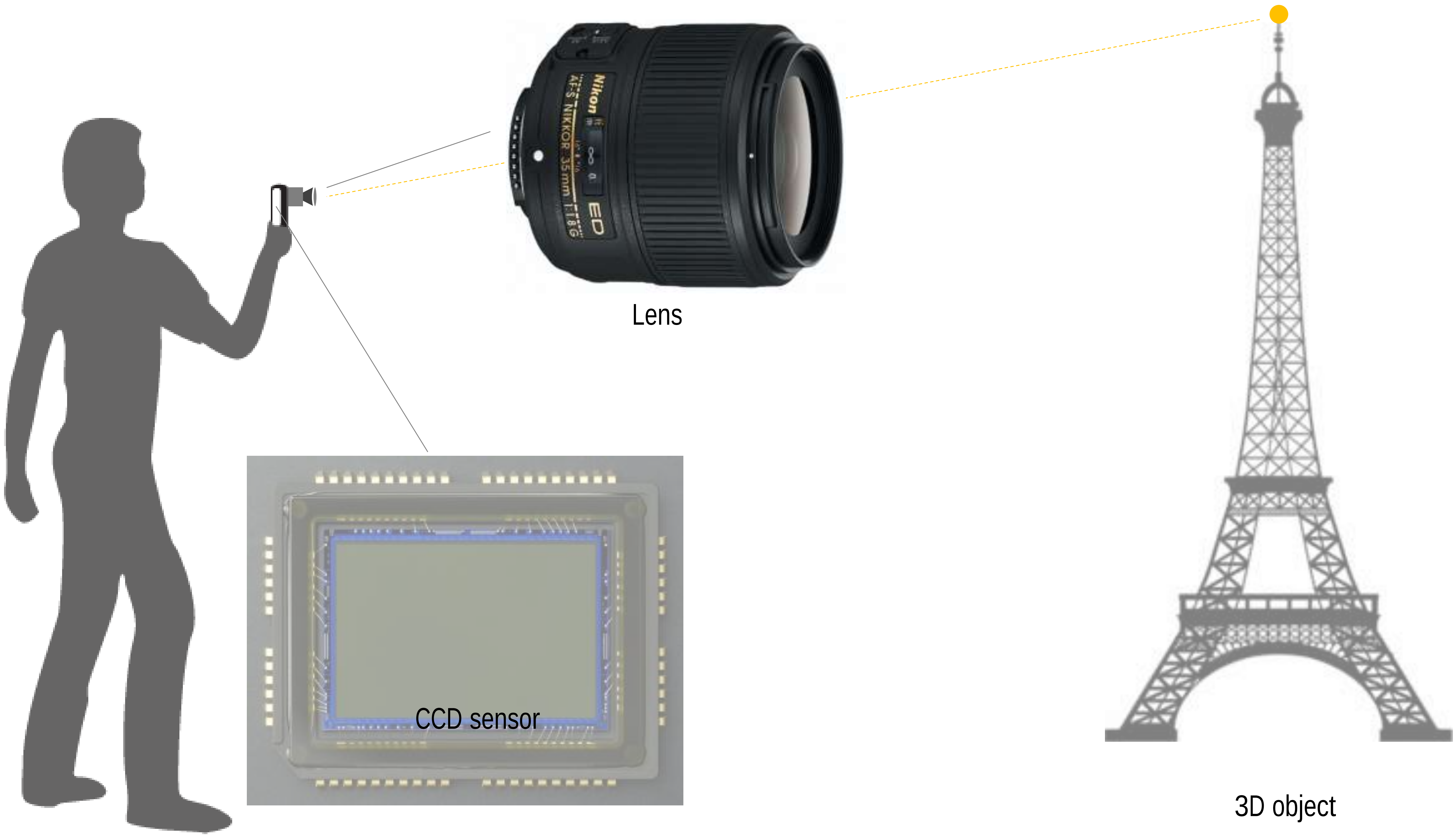
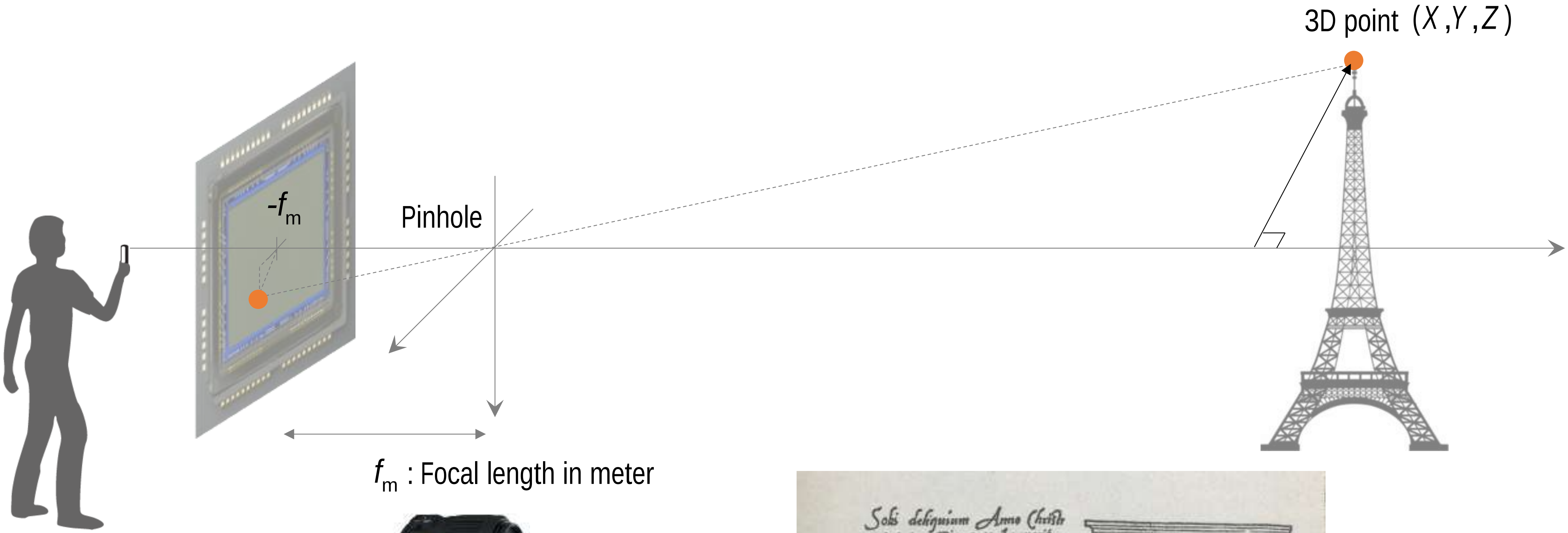
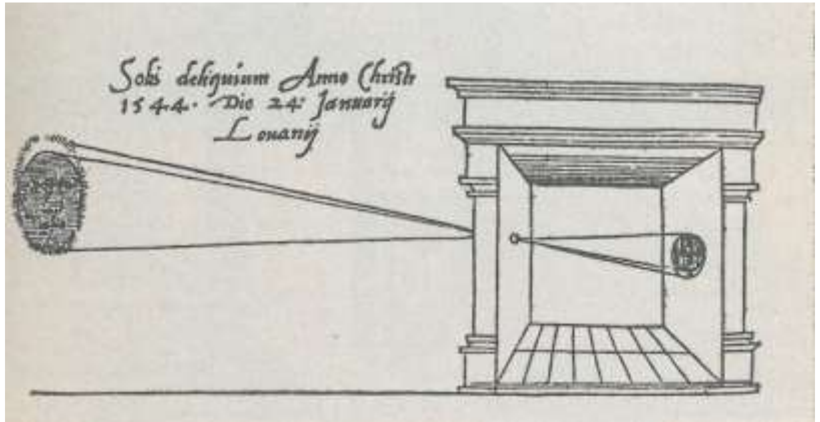
Camera Model



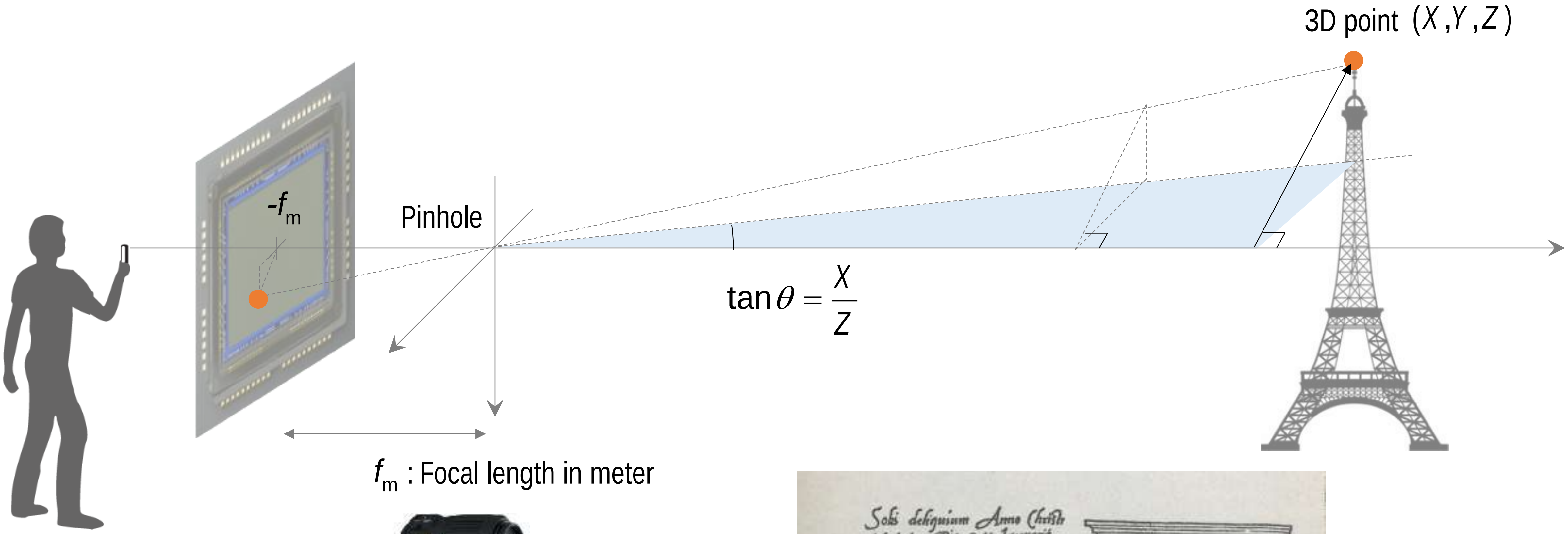
Lens
CCD sensor
3D object

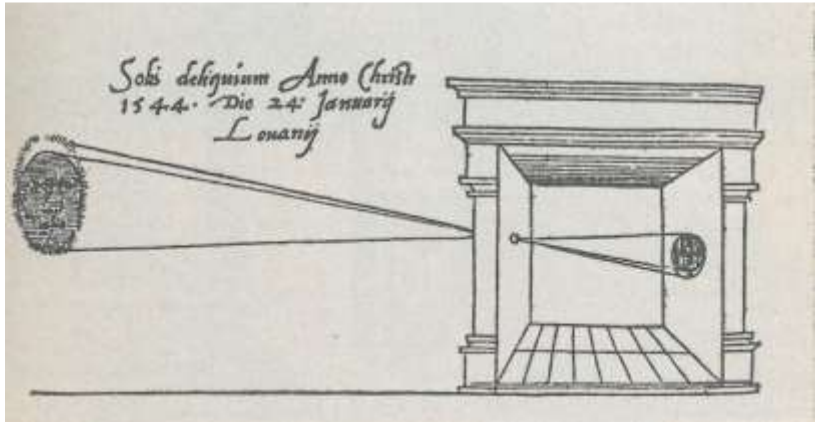
3D Point Projection (Metric Space)



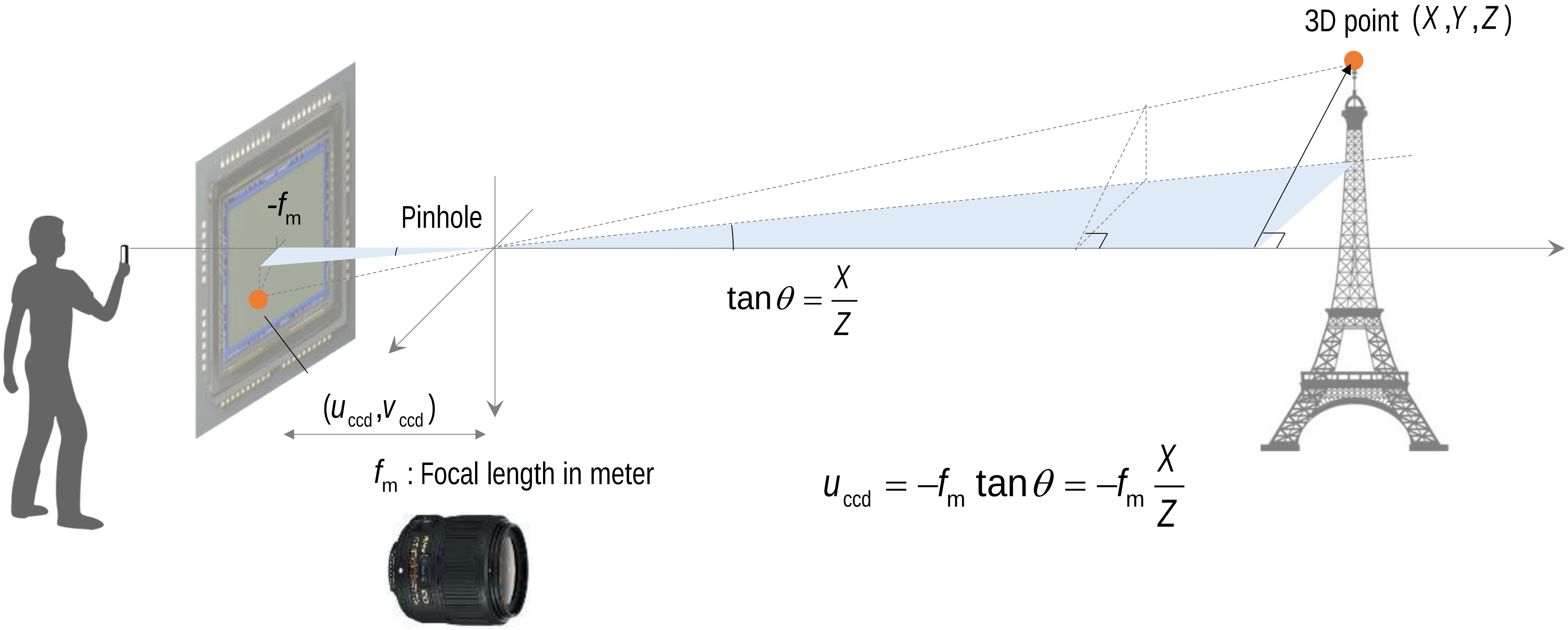


3D Point Projection (Metric Space)





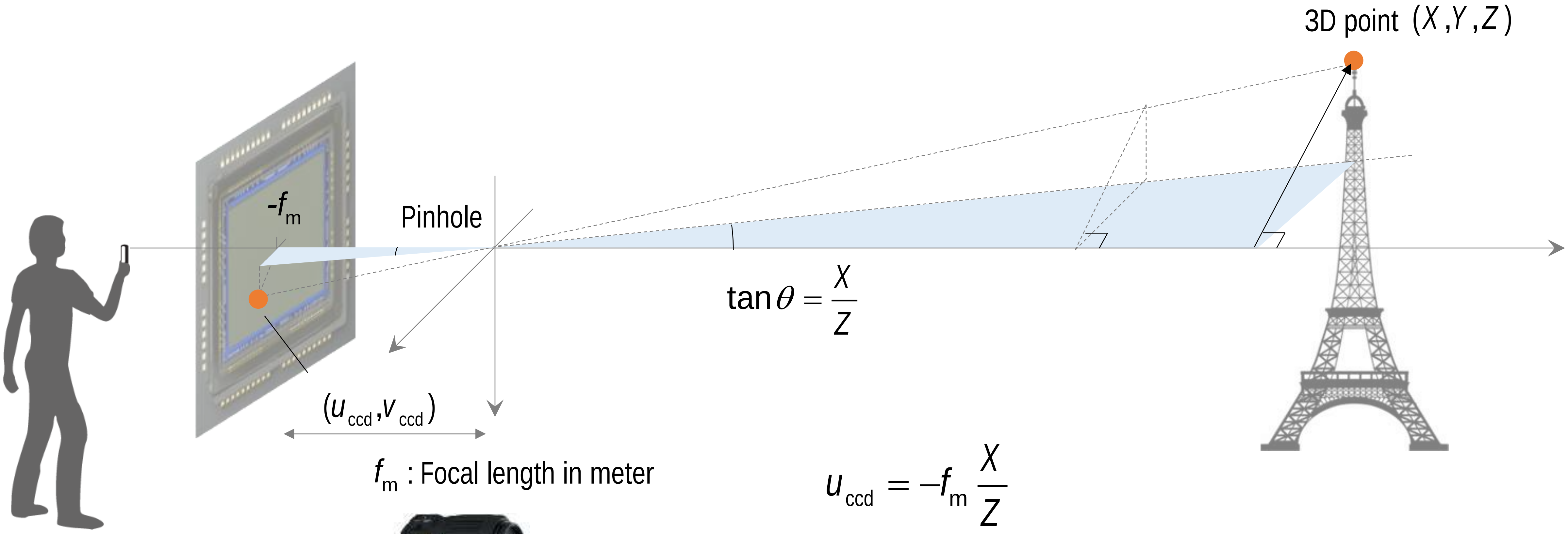
3D Point Projection (Metric Space)



$$\tan\theta = \frac{X}{Z}$$

$$u_{ccd} = -f_m \tan\theta = -f_m \frac{X}{Z}$$

3D Point Projection (Metric Space)

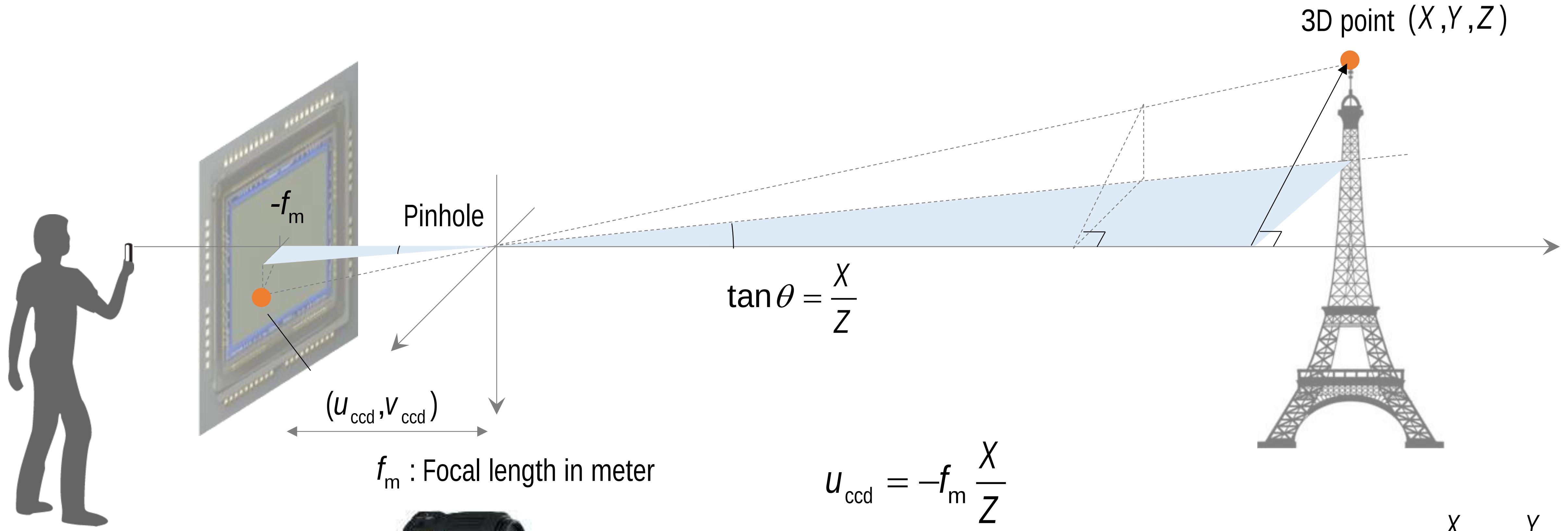


f_m : Focal length in meter

$$u_{ccd} = -f_m \frac{X}{Z}$$

$$v_{ccd} = -f_m \frac{Y}{Z}$$

3D Point Projection (Metric Space)



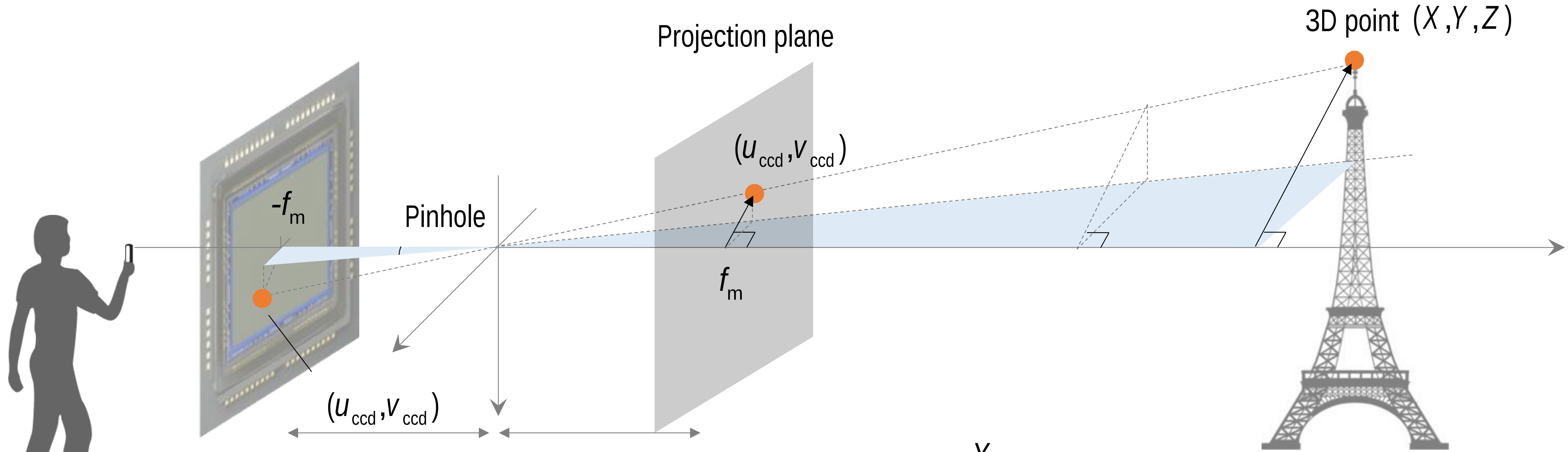
$$u_{ccd} = -f_m \frac{X}{Z}$$

$$v_{ccd} = -f_m \frac{Y}{Z}$$

$$(X, Y, Z) \rightarrow (u_{ccd}, v_{ccd}) = (-f_m \frac{X}{Z}, -f_m \frac{Y}{Z})$$

2D projection onto CCD plane

3D Point Projection (Metric Space)



f_m : Focal length in meter

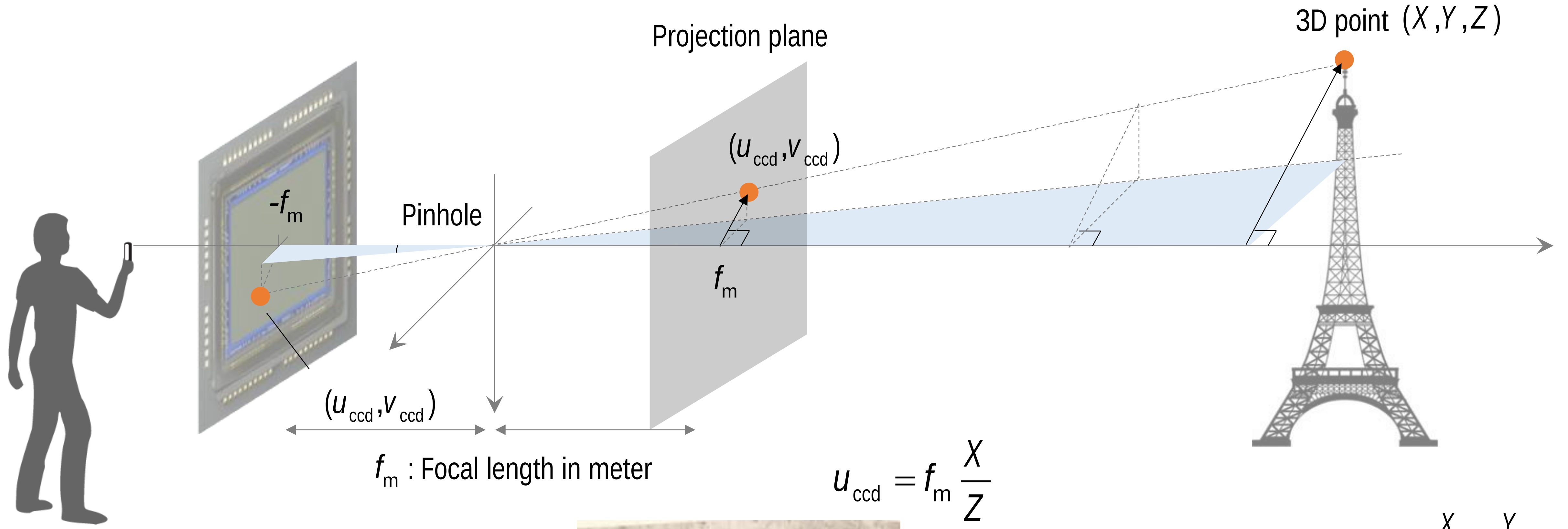
$$u_{ccd} = f_m \frac{X}{Z}$$

$$v_{ccd} = f_m \frac{Y}{Z}$$

$$(X, Y, Z) \rightarrow \quad (u_{ccd}, v_{ccd}) = (f_m \frac{X}{Z}, f_m \frac{Y}{Z})$$

2D projection onto CCD plane

3D Point Projection (Metric Space)

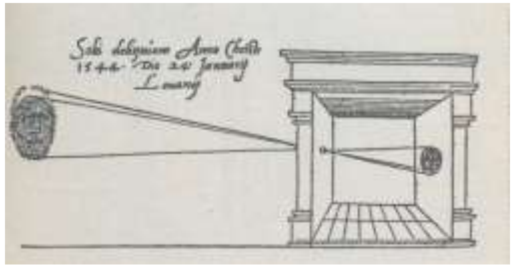


$$u_{ccd} = f_m \frac{X}{Z}$$

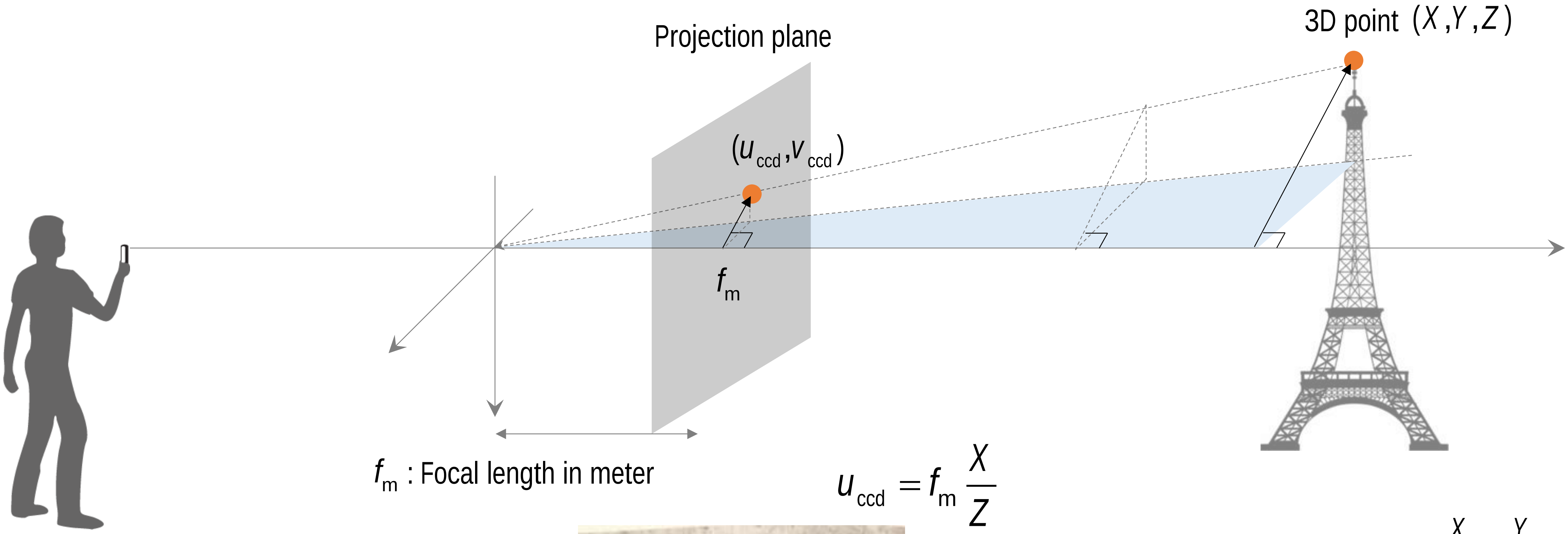
$$= f_m \frac{Y}{Z}$$

$$(X,Y,Z) \rightarrow (u_{ccd}, v_{ccd}) = (f_m \frac{X}{Z}, f_m \frac{Y}{Z})$$

2D projection onto CCD plane



3D Point Projection (Metric Space)



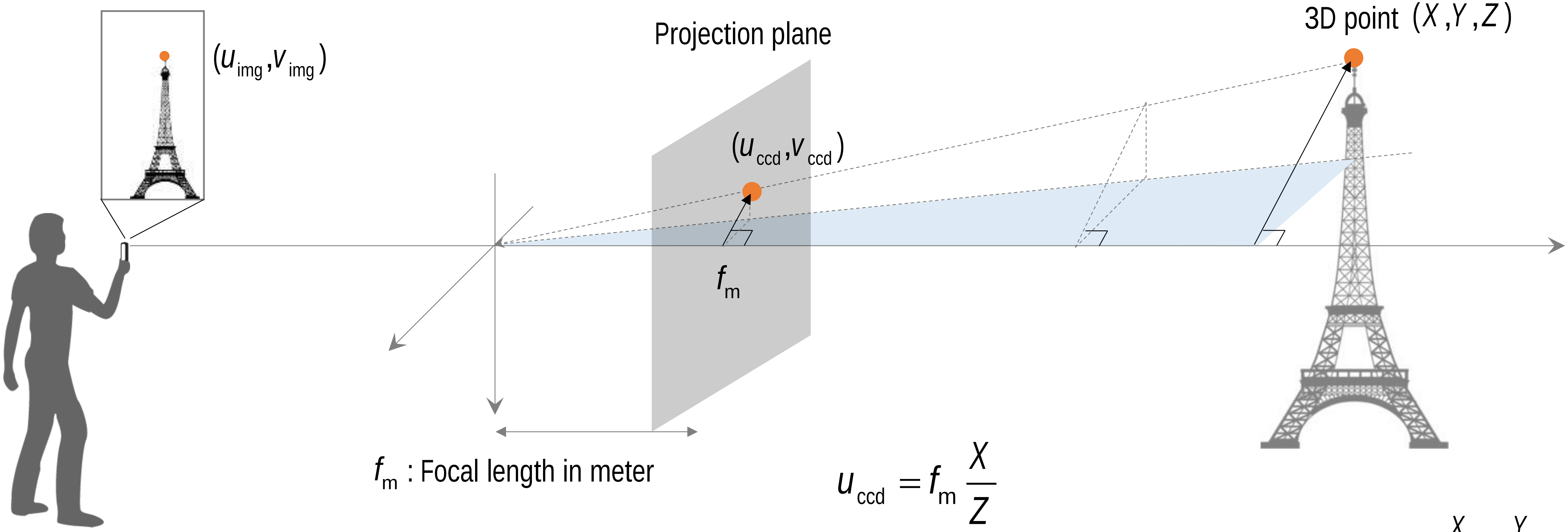
$$u_{ccd} = f_m \frac{X}{Z}$$

$$= f_m \frac{Y}{Z}$$

$$(X, Y, Z) \rightarrow \quad (u_{ccd}, v_{ccd}) = (f_m \frac{X}{Z}, f_m \frac{Y}{Z})$$

2D projection onto CCD plane

3D Point Projection (Metric Space)



$$u_{ccd} = f_m \frac{X}{Z}$$

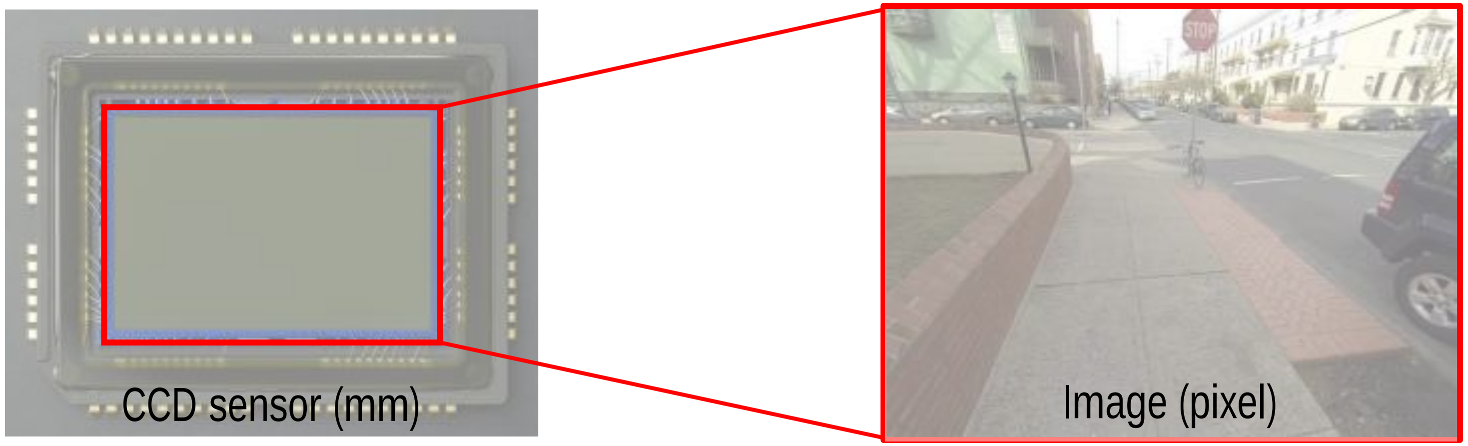
$$v_{ccd} = f_m \frac{Y}{Z}$$

$$\underbrace{(u_{img}, v_{img})}_{\text{Pixel}} \sim \underbrace{(u_{ccd}, v_{ccd})}_{\text{Metric}} \quad ?$$

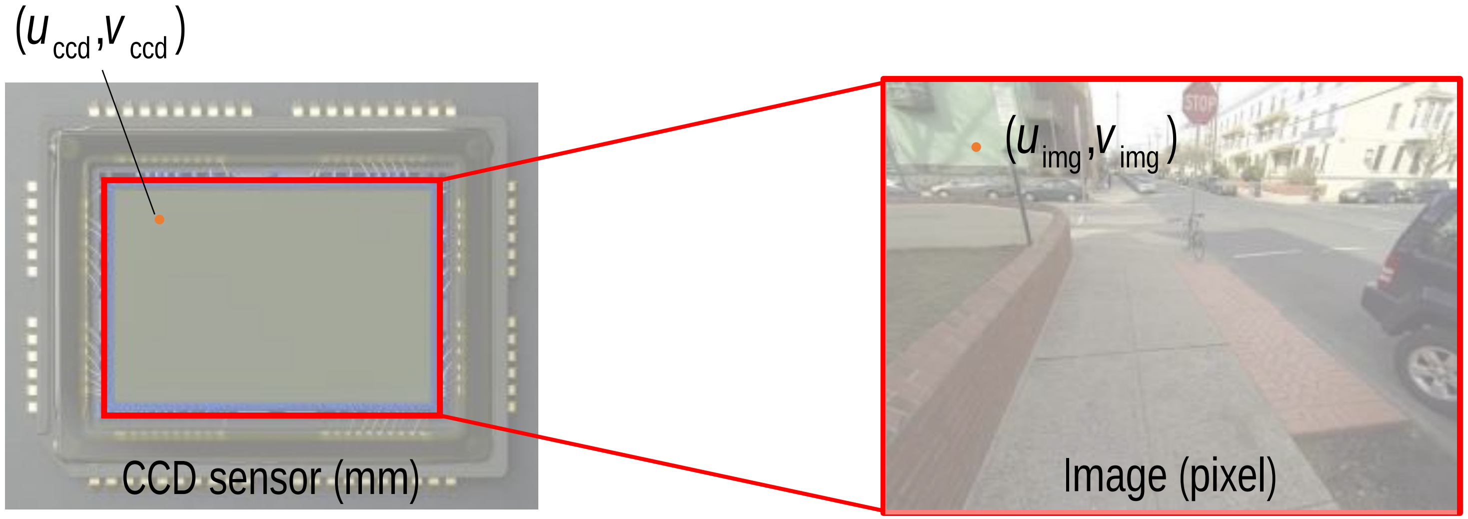
$$(X, Y, Z) \rightarrow \quad (u_{ccd}, v_{ccd}) = (f_m \frac{X}{Z}, f_m \frac{Y}{Z})$$

2D projection onto CCD plane

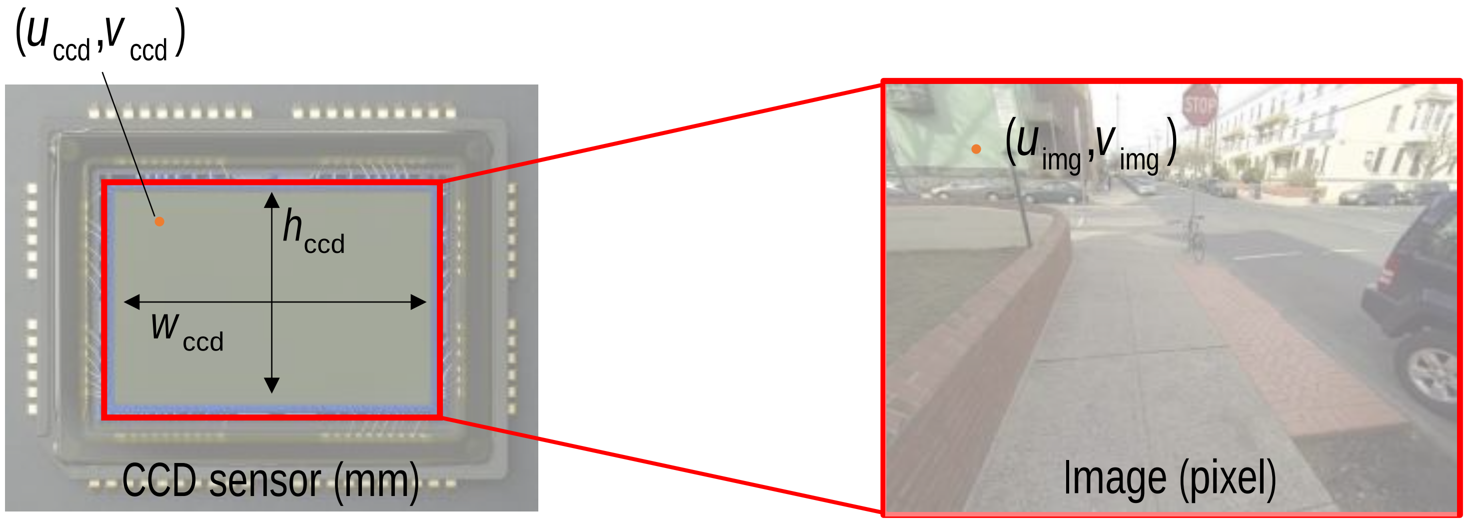
3D Point Projection (Pixel Space)



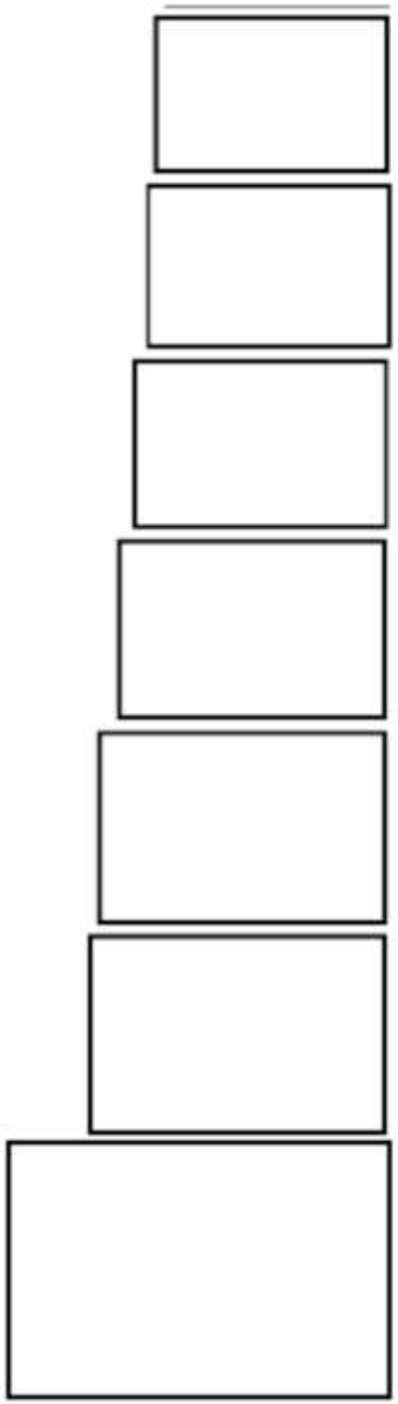
3D Point Projection (Pixel Space)



3D Point Projection (Pixel Space)

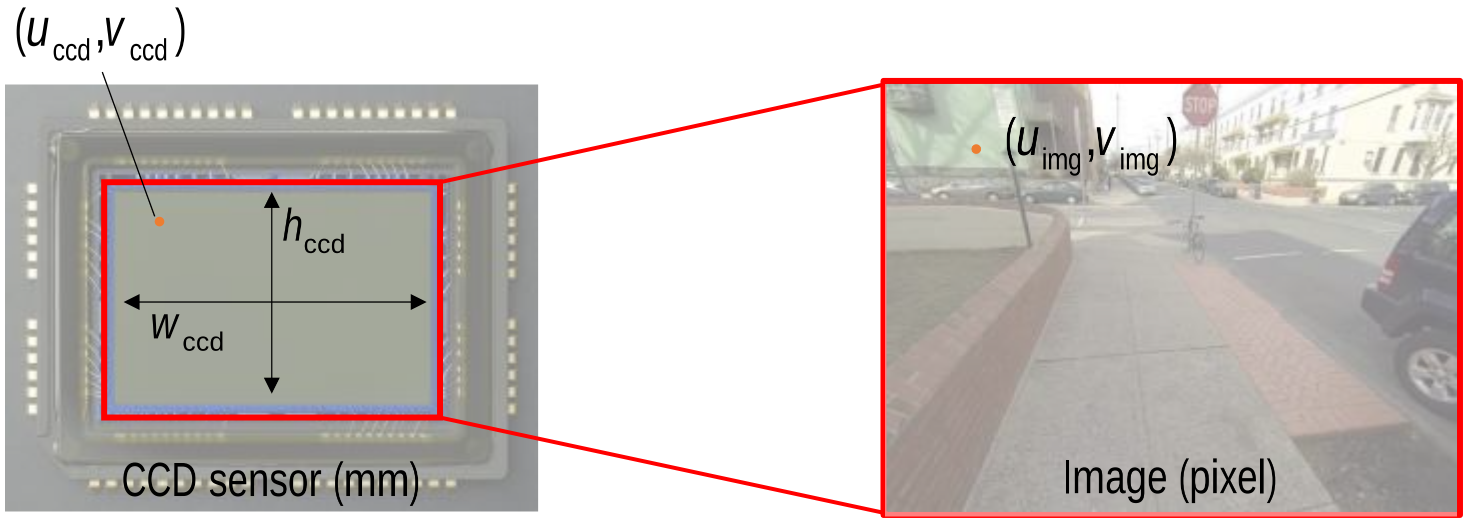


Imager Sizes	Formats (Type)	~Diag.	Uses
	1/7" - 1.85 x 1.39mm	2.3	Cell phones, web cams, etc....
	1/6" - 2.15 x 1.61mm	2.7	Cell phones, web cams, etc....
	1/5" - 2.55 x 1.91mm	3.2	Cell phones, web cams, etc....
	1/4" - 3.2 x 2.4mm	4.0	Cell phones, web cams, etc....
	1/3.6" - 4.0 x 3.0mm	5.0	P&S DSC
	1/3.2" - 4.536 x 3.416mm	5.678	P&S DSC
	1/3" - 4.8 x 3.6mm	6.0	Casio QV-8000SX (1.2MP), Epson PhotoPC 700 (1.2MP)
	1/2.7" - 5.27 x 3.96mm	6.592	Canon PowerShot A20 (1.92MP), HP PhotoSmart C618 (1.92)
	1/2" - 6.4 x 4.8mm	8.0	Olympus C-2100Z (1.92MP), Epson PhotoPC 850Z (1.92)
	1/1.8" - 7.176 x 5.319mm	8.932	Nikon Coolpix 995 (3.14MP), Olympus C-4040Z (3.9MP), Canon PowerShot G2 (3.8MP), Sony DSC-S85 (3.8MP)
	2/3" - 8.8 x 6.6mm	11.0	Nikon Coolpix 5000 (4.92MP), Sony DSC-F707 (4.92MP), Olympus E-10 (3.7MP), Minolta DiMAGE 7 (4.92MP)
	1" - 12.8 x 9.6mm	16.0	Not used in DSCs. Used in some high-end video cameras
	Kodak KAF-5100CE CCD 17.8 x 13.4mm (4/3")	22.28	Olympus announced deveolpment of a new camera and new lenses for this 4/3" size. 2614 x 1966 - 5.1MP - 6.8µm pixel
	Foveon X3 F7-35X3-A25B 20.7 x 13.8mm	24.9	Sigma SD9 (X3) 2268 x 1512 = 3.43MP - 9.12µm pixel 1.74x Focal Length Multiplier (35mm film)

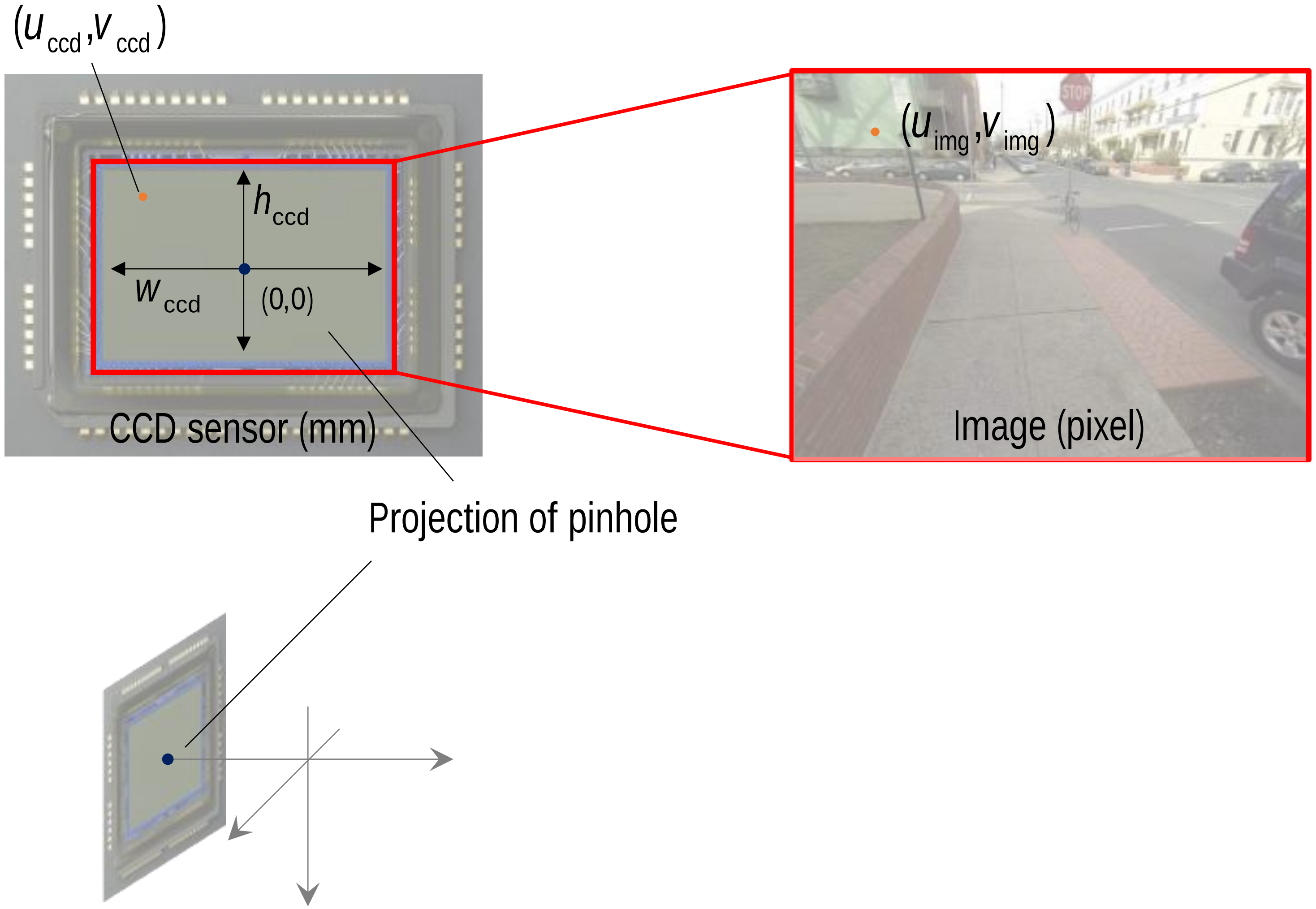


Canon D30 CMOS 21.8 x 14.5mm	26.2	Canon D30 2160 x 1440 = 3.11MP - 10.1µm pixel 1.65x Focal Length Multiplier (35mm film)
Canon D60 CMOS 22.7 x 15.1mm	27.3	Canon D60 3072 x 2048 = 6.3MP - 7.4µm pixel 1.59x Focal Length Multiplier (35mm film)
Nikon D100 CCD Nikon D1x CCD 23.7 x 15.6mm	28.2	Nikon D100 - 3008 x 2000 = 6.1MP - 7.8µm pixel Nikon D1x - 4024 x 1324 = 5.24MP - 5.9 x 11.7µm pixel 1.52x Focal Length Multiplier (35mm film)
APS Film 25.1 x 16.7mm	30.148	APS cameras 1.44x Focal Length Multiplier (35mm film)
Canon EOS-1D CCD 27.0 x 17.8mm	32.3	Canon EOS-1D 2464 x 1648 = 4.06MP - 10.8µm pixel 1.34x Folcal Length Multiplier (35mm Film)
Kodak KAF-6303CE CCD 27.8 x 18.5mm	33.4	Kodak 760 3088 x 2056 = 6.35MP - 9.0µm pixel 1.30x Focal Length Multiplier (35mm film)
35mm Film Canon 1Ds Kodak 14n 36.0 x 24.0mm	43.27	35mm film cameras Canon 1Ds - 4064 x 2704 = 10.99MP - 8.85µm pixel Kodak DCS Pro 14n - 4536 x 3024 = 13.7MP - 7.94µm pixel

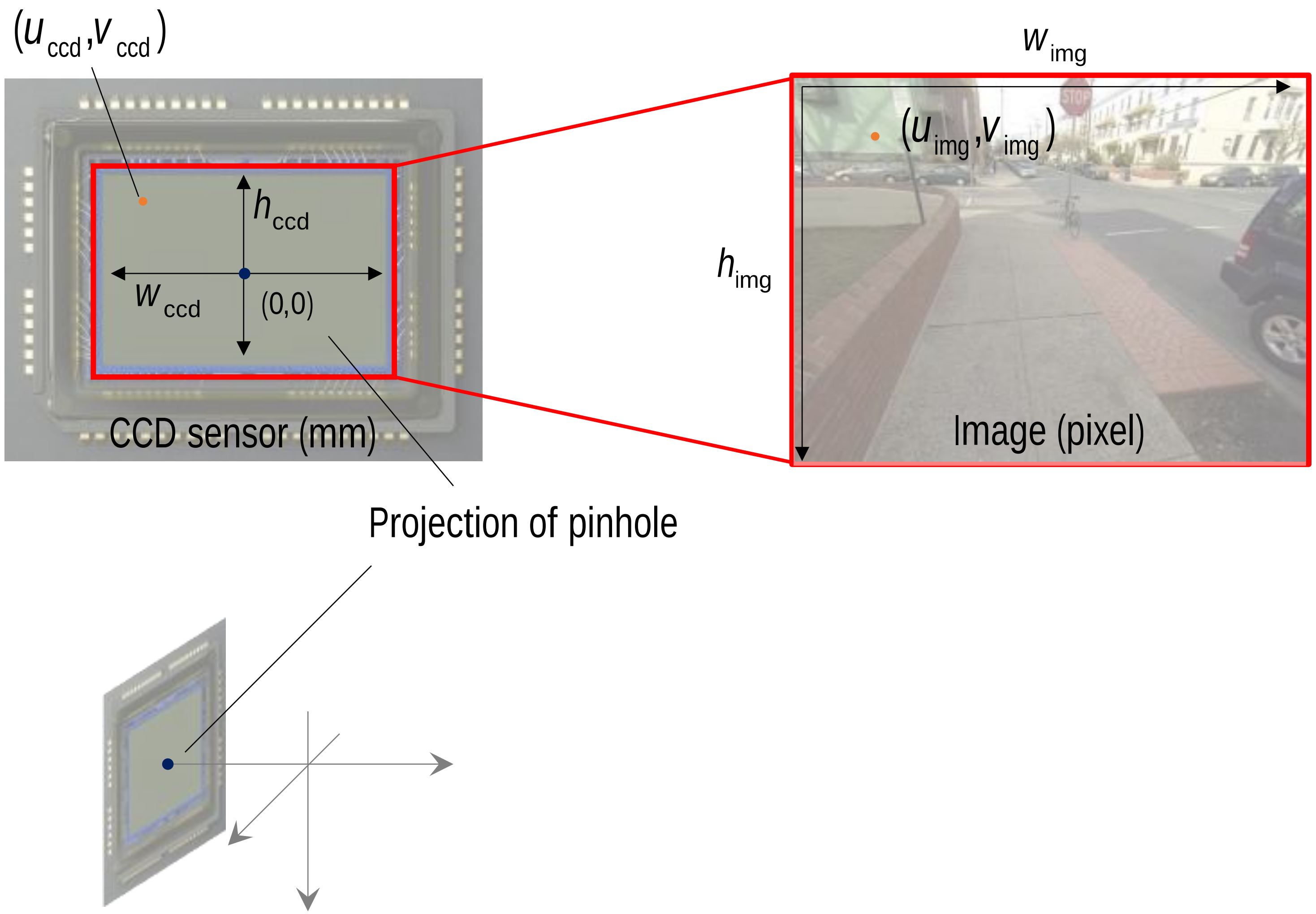
3D Point Projection (Pixel Space)



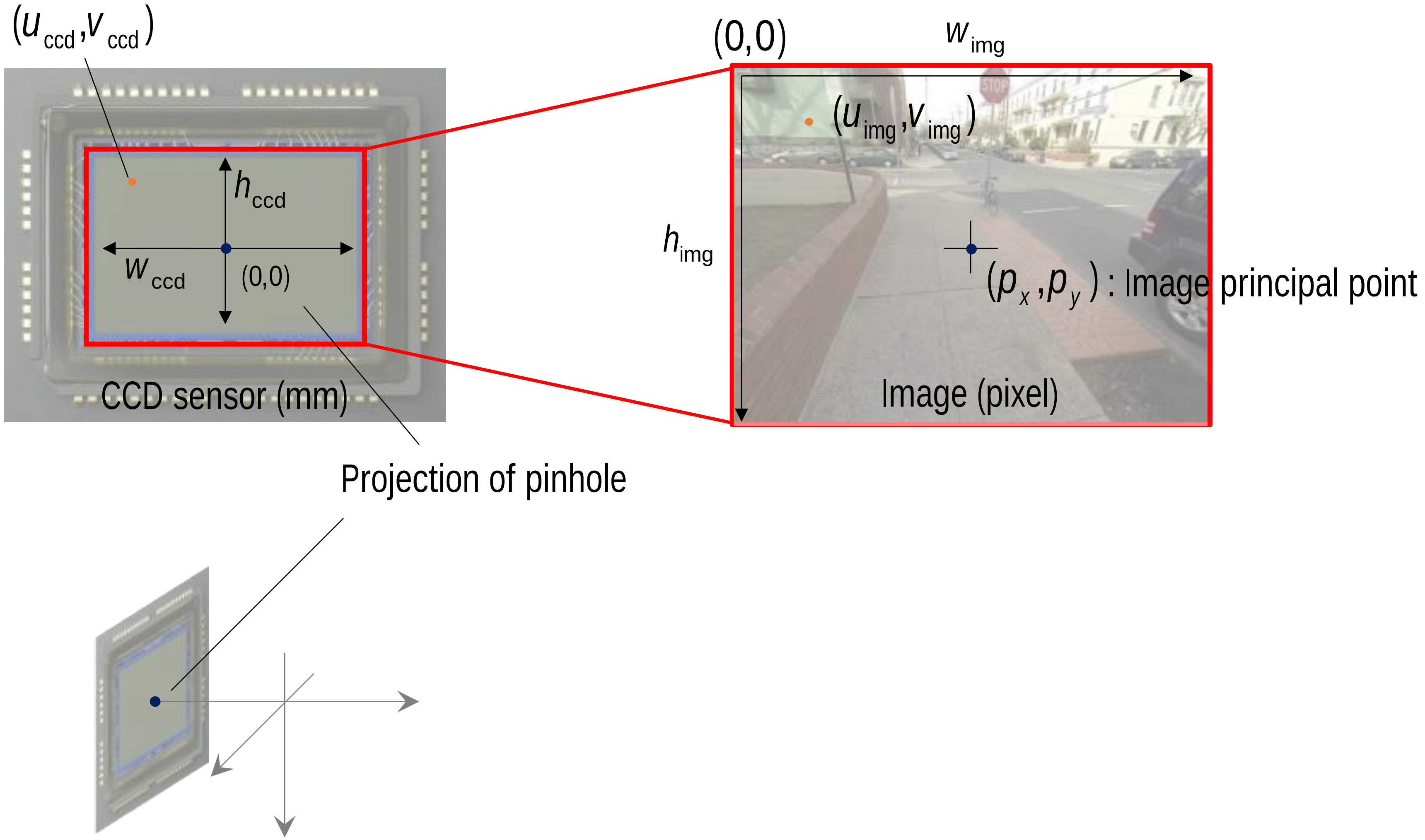
3D Point Projection (Pixel Space)



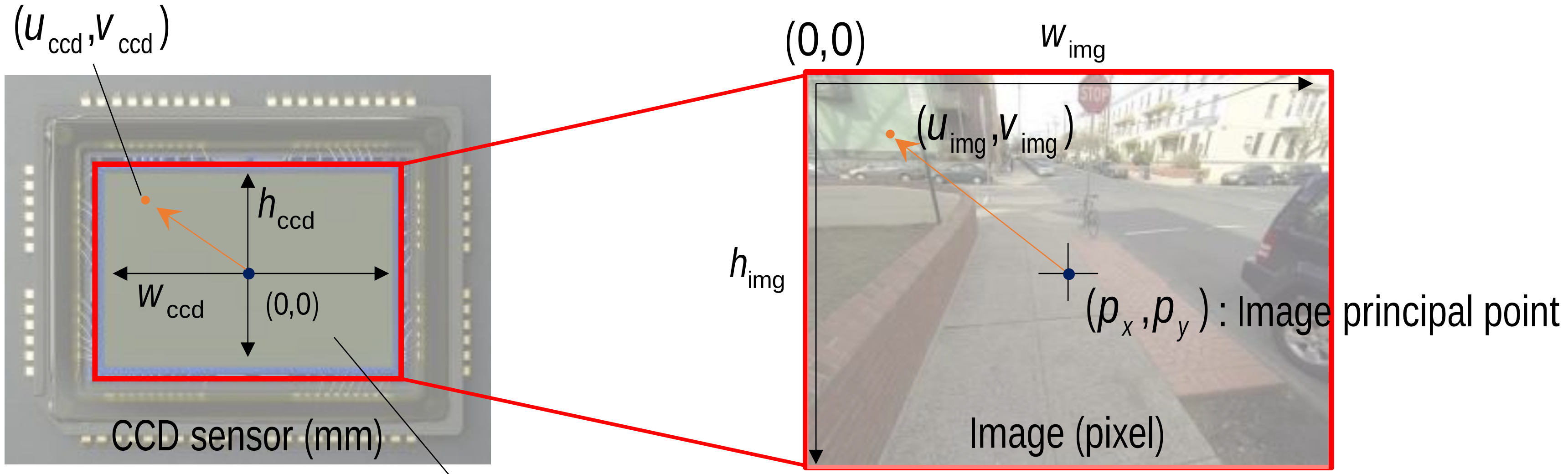
3D Point Projection (Pixel Space)

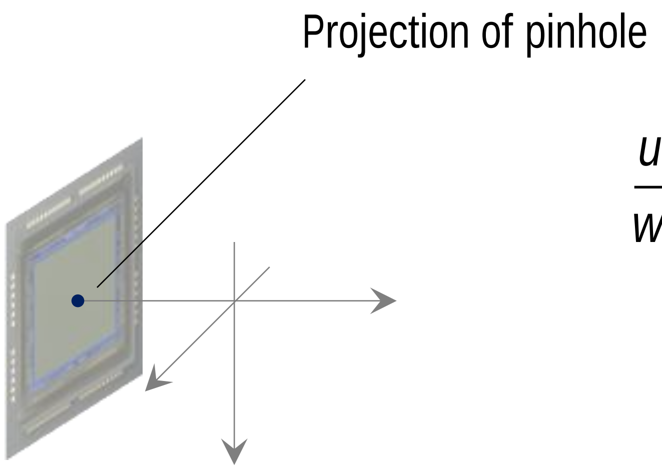


3D Point Projection (Pixel Space)



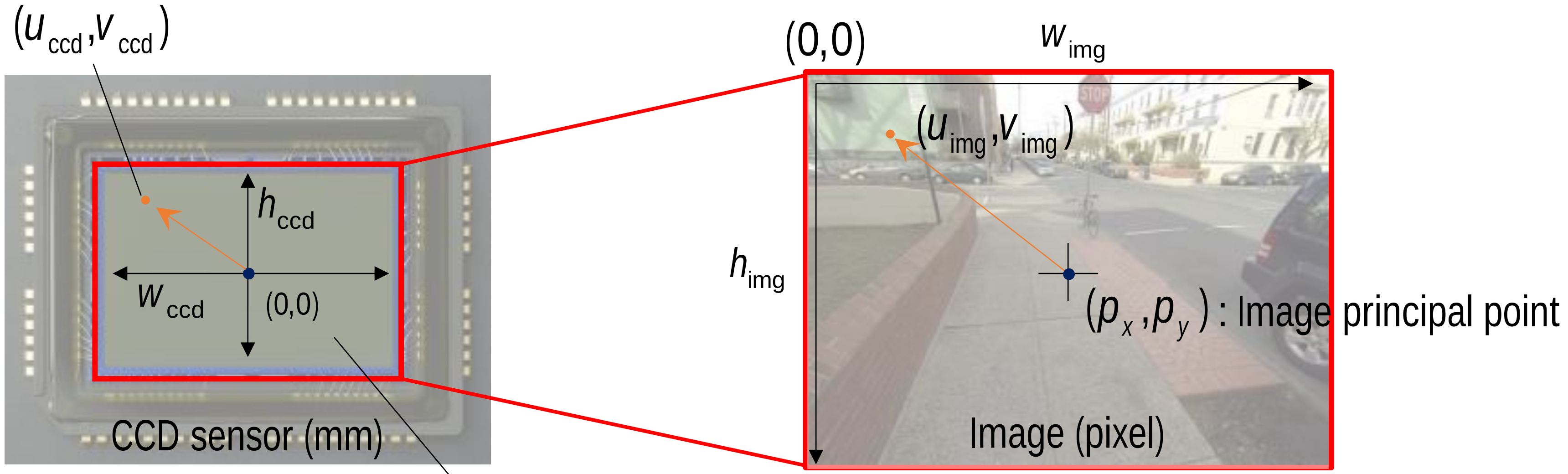
3D Point Projection (Pixel Space)



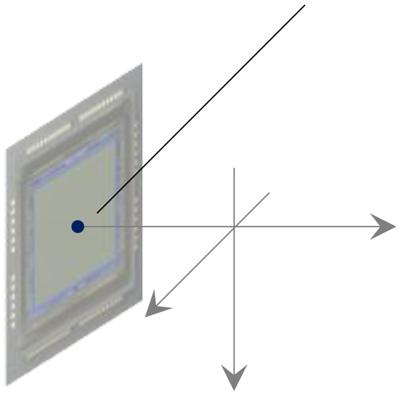


$$\frac{u_{ccd}}{w_{ccd}} = \frac{u_{img} - p_x}{w_{img}}$$

3D Point Projection (Pixel Space)

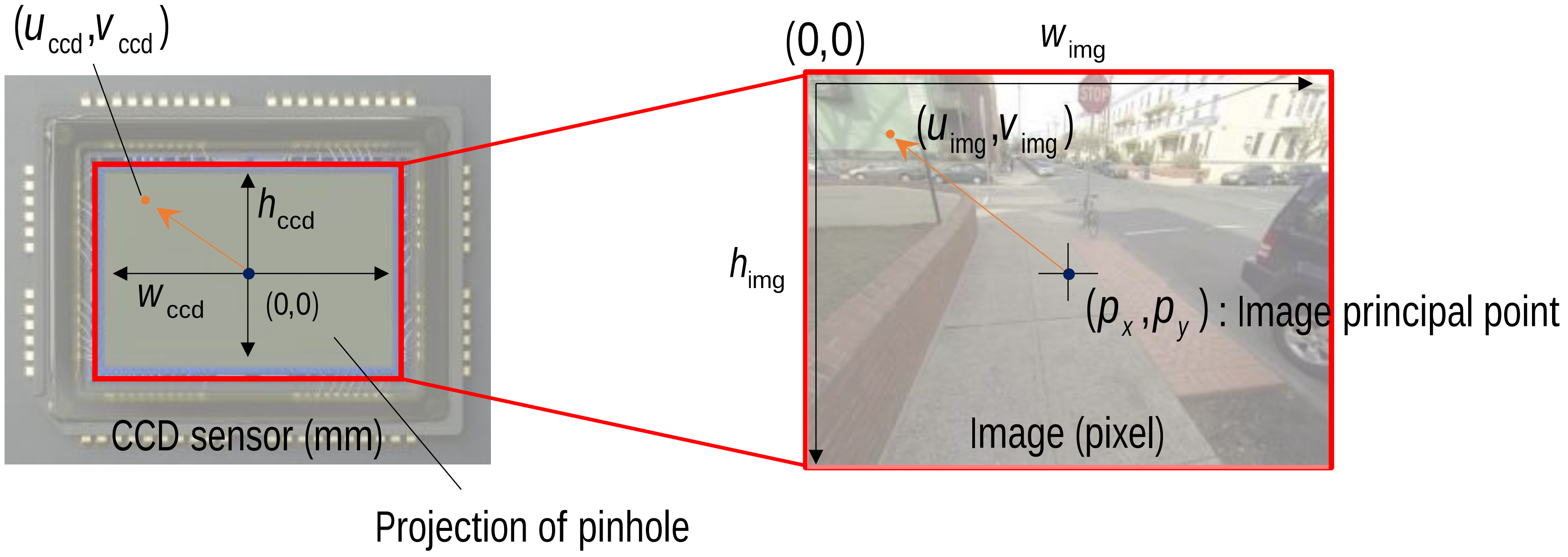


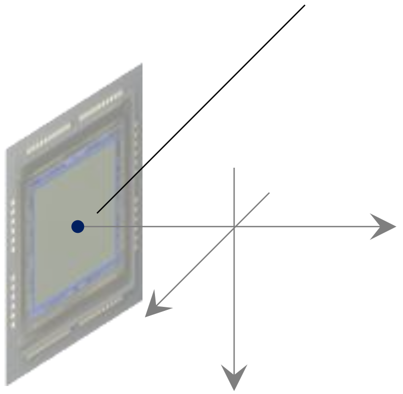
Projection of pinhole



$$\frac{u_{ccd}}{w_{ccd}} = \frac{u_{img} - p_x}{w_{img}} \qquad \frac{v_{ccd}}{h_{ccd}} = \frac{v_{img} - p_y}{h_{img}}$$

3D Point Projection (Pixel Space)

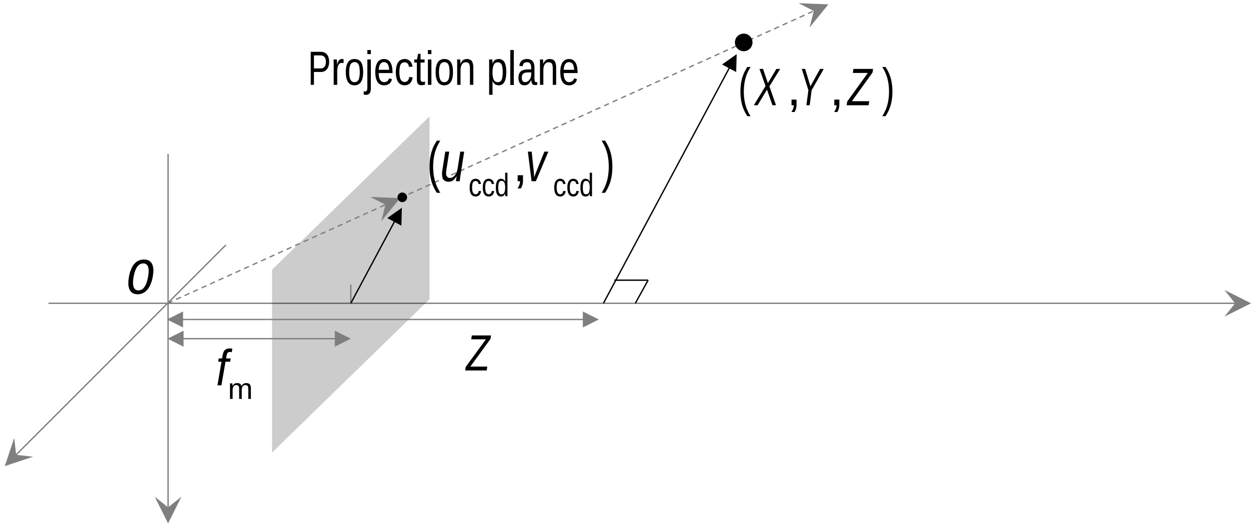




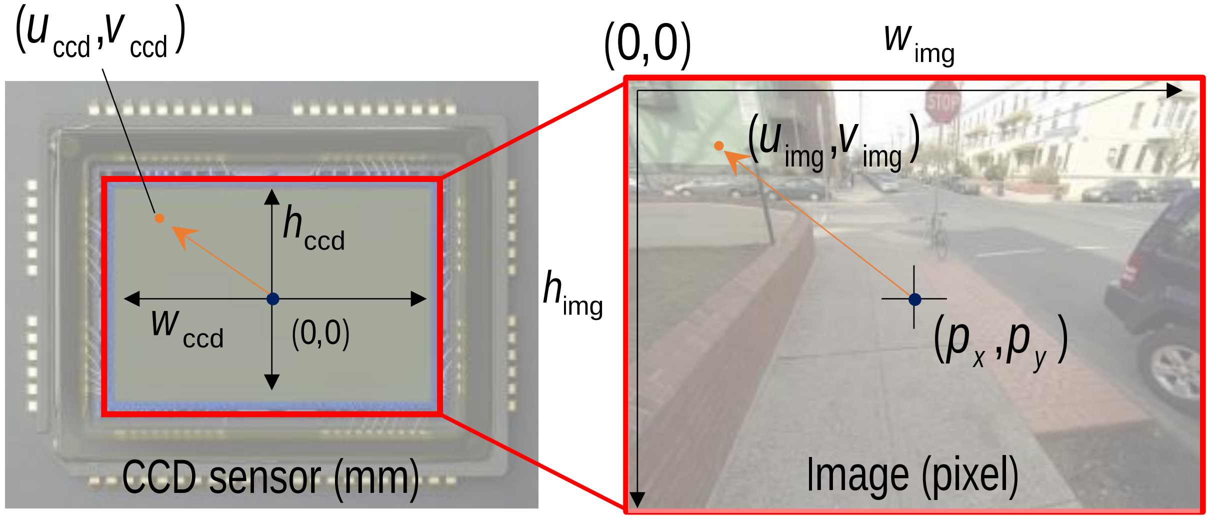
$$\frac{u_{ccd}}{w_{ccd}} = \frac{u_{img} - p_x}{w_{img}} \qquad \frac{v_{ccd}}{h_{ccd}} = \frac{v_{img} - p_y}{h_{img}}$$

$$\rightarrow \quad u_{img} = u_{ccd}\frac{w_{img}}{w_{ccd}} + p_x \qquad v_{img} = v_{ccd}\frac{h_{img}}{h_{ccd}} + p_y$$

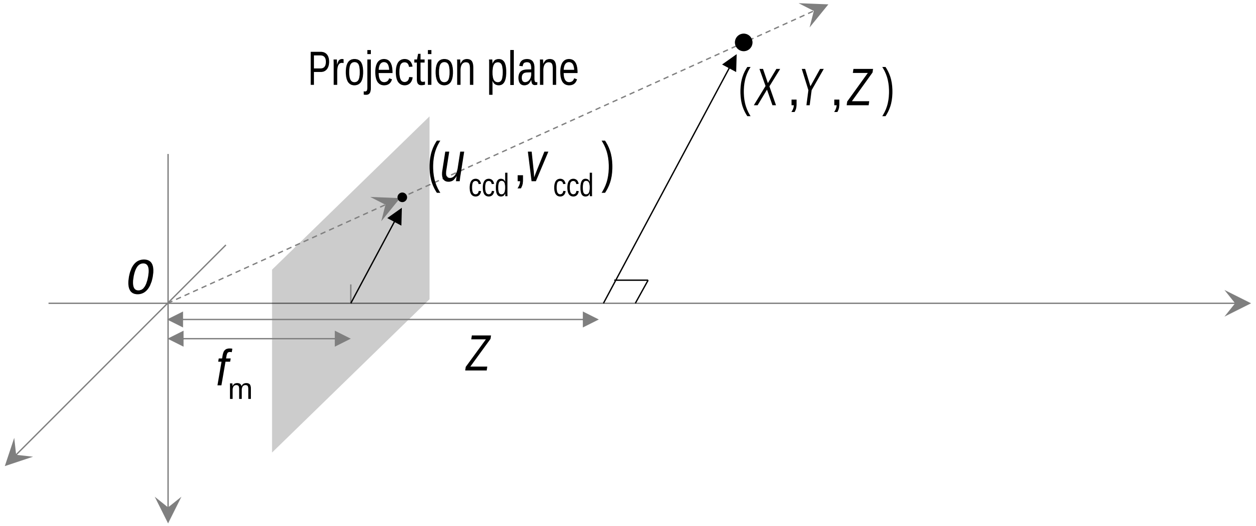
3D Point Projection (Pixel Space)



$$(u_{ccd}, v_{ccd}) = (f_m \frac{X}{Z}, f_m \frac{Y}{Z})$$: Metric projection



3D Point Projection (Pixel Space)

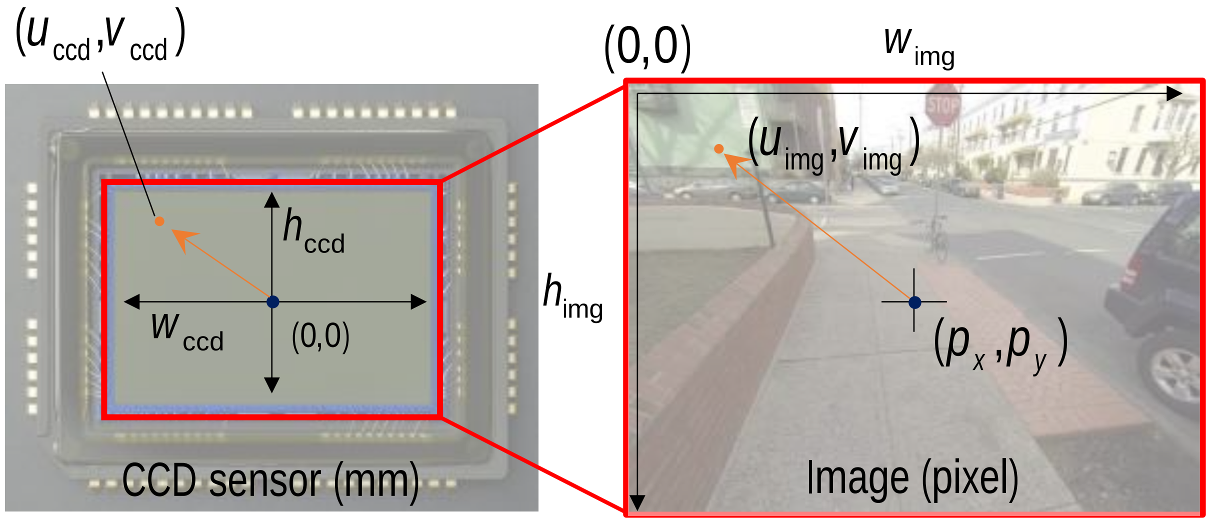


$$(u_{ccd}, v_{ccd}) = (f_m \frac{X}{Z}, f_m \frac{Y}{Z})$$: Metric projection

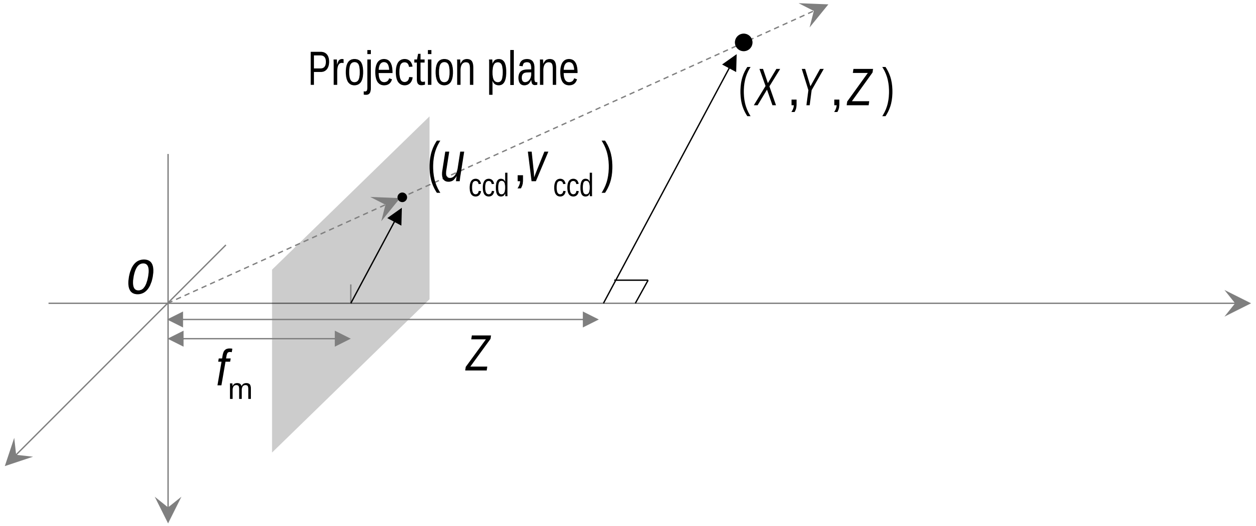
Pixel projection

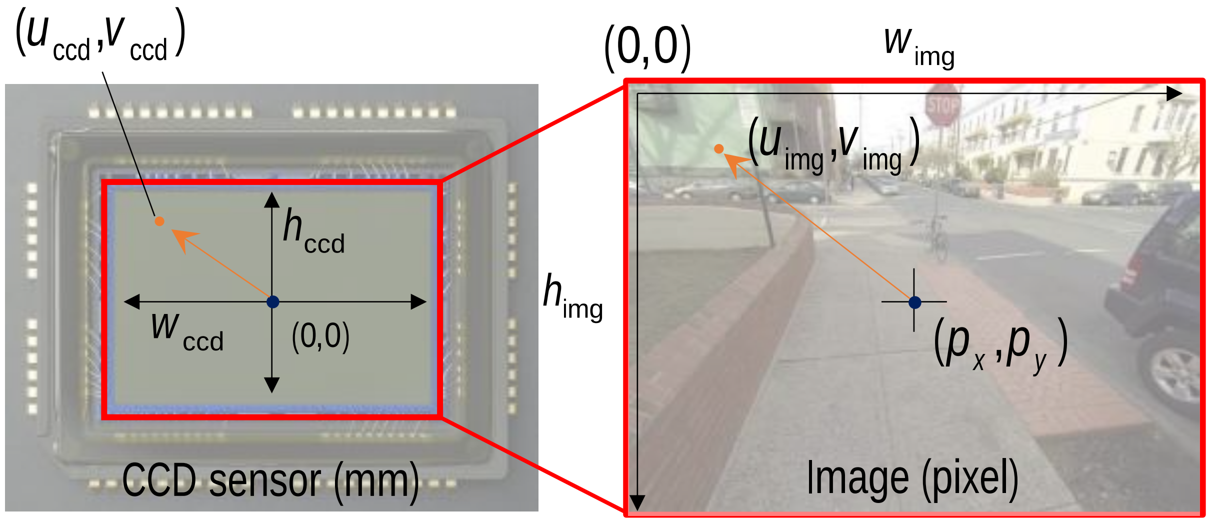
$$\rightarrow \quad u_{img} = u_{ccd} \frac{w_{img}}{w_{ccd}} + p_x$$

$$v_{img} = v_{ccd} \frac{h_{img}}{h_{ccd}} + p_y$$



3D Point Projection (Pixel Space)





$$(u_{\text{ccd}}, v_{\text{ccd}}) = \left(f_{\text{m}}\frac{X}{Z}, f_{\text{m}}\frac{Y}{Z}\right)$$: Metric projection

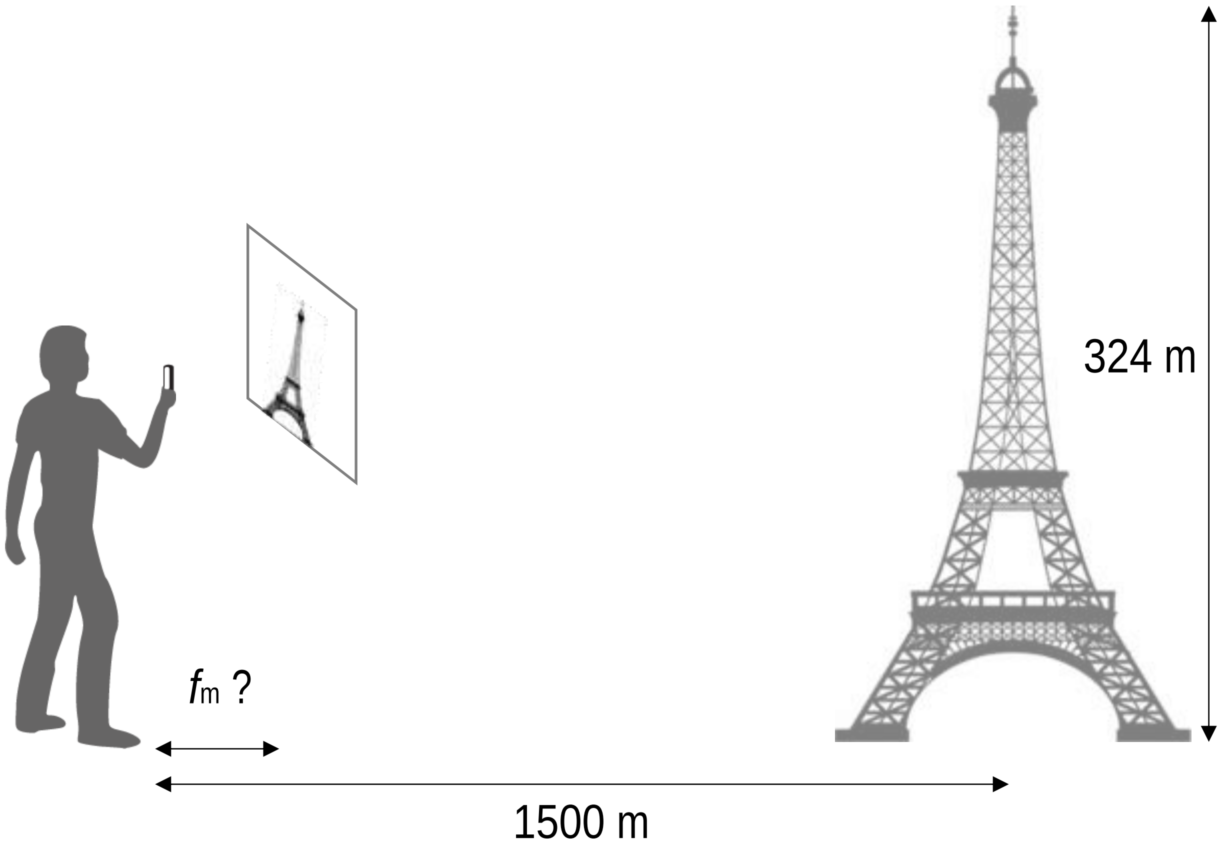
Pixel projection

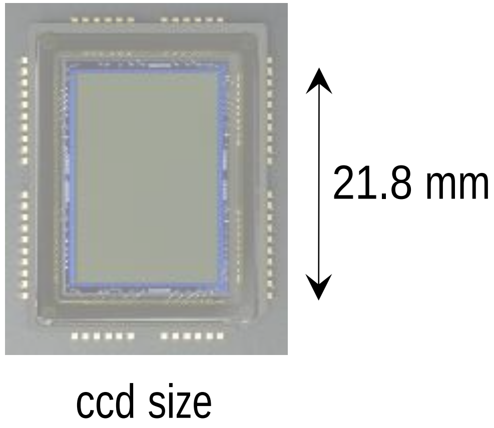
$$\longrightarrow u_{\text{img}} = u_{\text{ccd}}\frac{w_{\text{img}}}{w_{\text{ccd}}} + p_x = f_{\text{m}}\frac{w_{\text{img}}}{w_{\text{ccd}}}\frac{X}{Z} + p_x$$

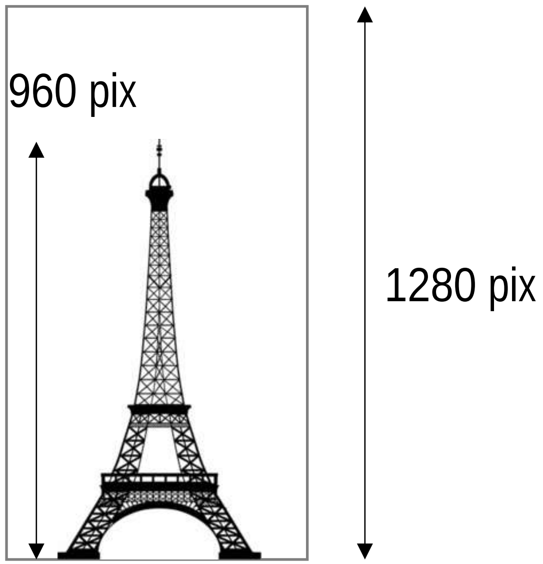
$$v_{\text{img}} = v_{\text{ccd}}\frac{h_{\text{img}}}{h_{\text{ccd}}} + p_y = f_{\text{m}}\frac{h_{\text{img}}}{h_{\text{ccd}}}\frac{Y}{Z} + p_y$$

What f to make the height of Eifel tower appear 960 pixel distance?

Exercise

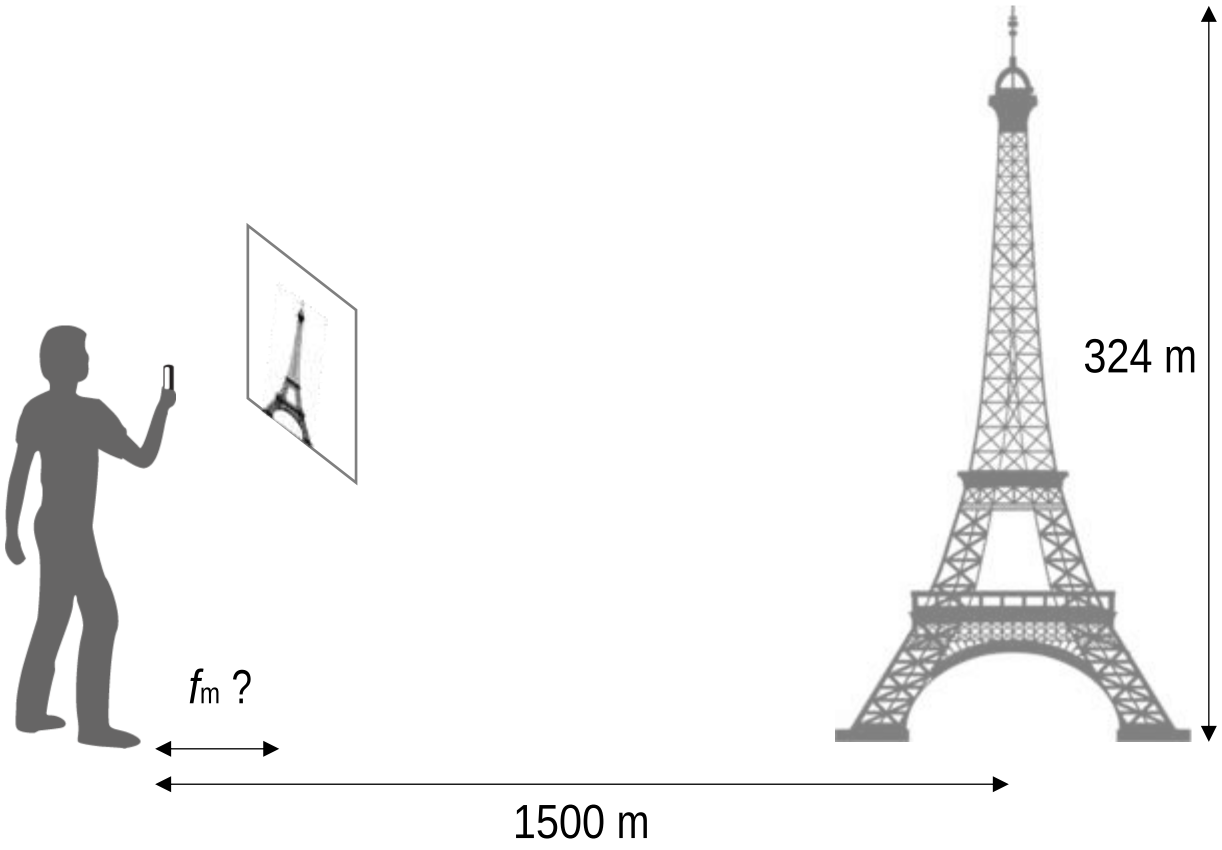


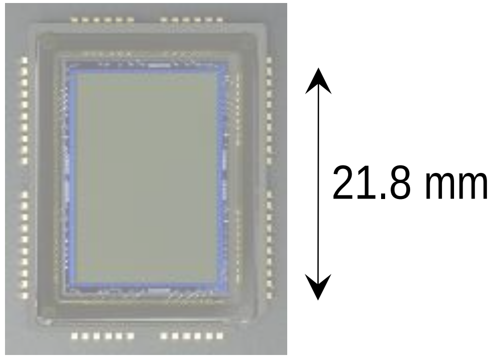




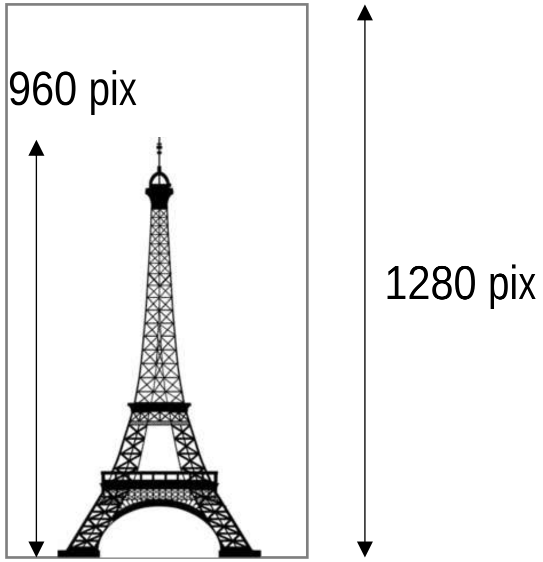
What f to make the height of Eifel tower appear 960 pixel distance?

Exercise





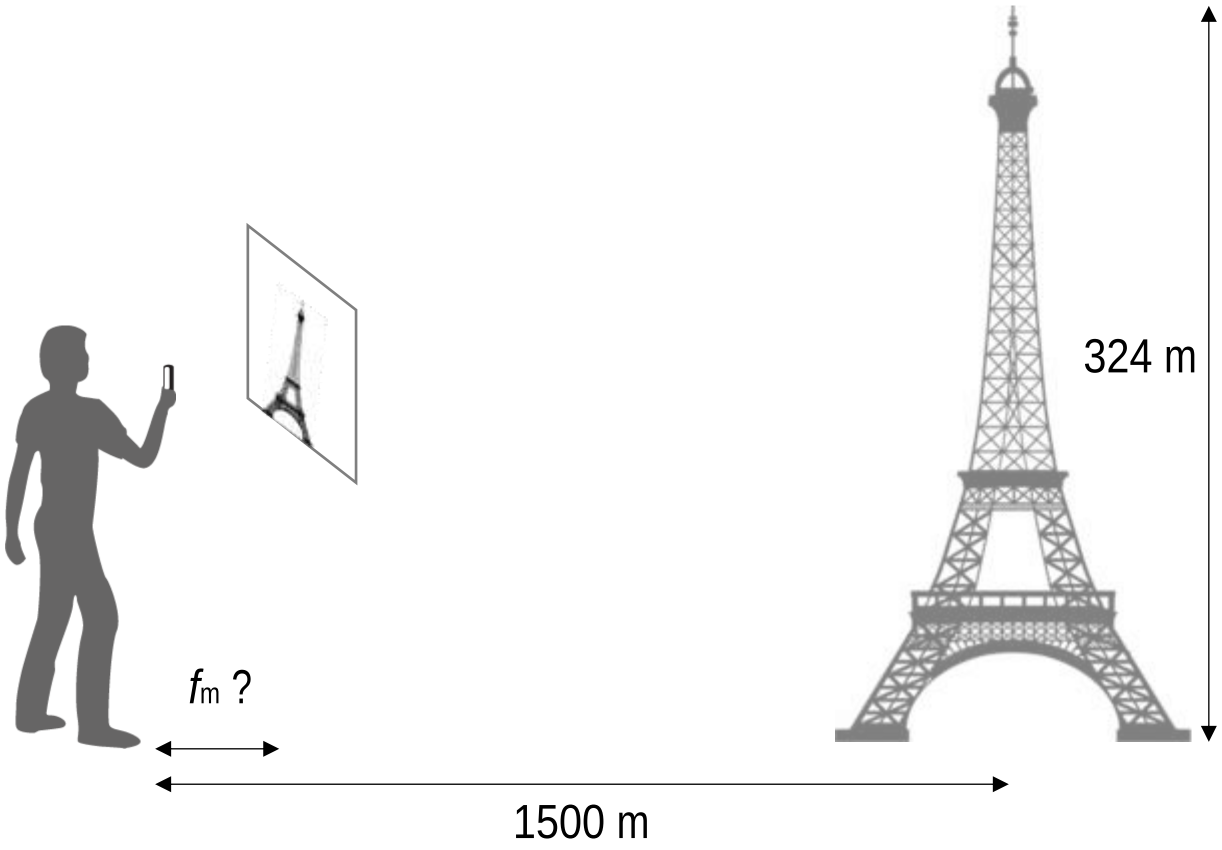
ccd size

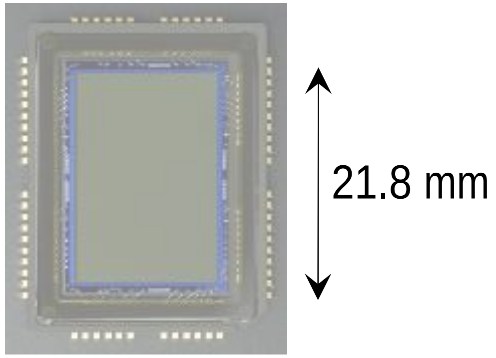


$$y_{img} = f_m \frac{h_{img}}{h_{ccd}} \frac{Y}{Z}$$

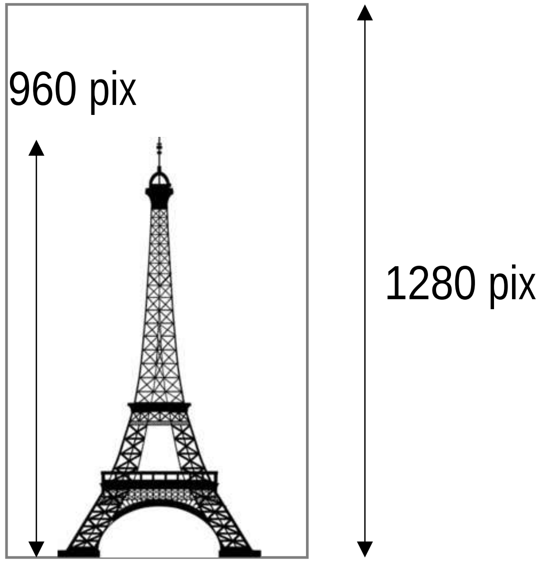
What f to make the height of Eifel tower appear 960 pixel distance?

Exercise





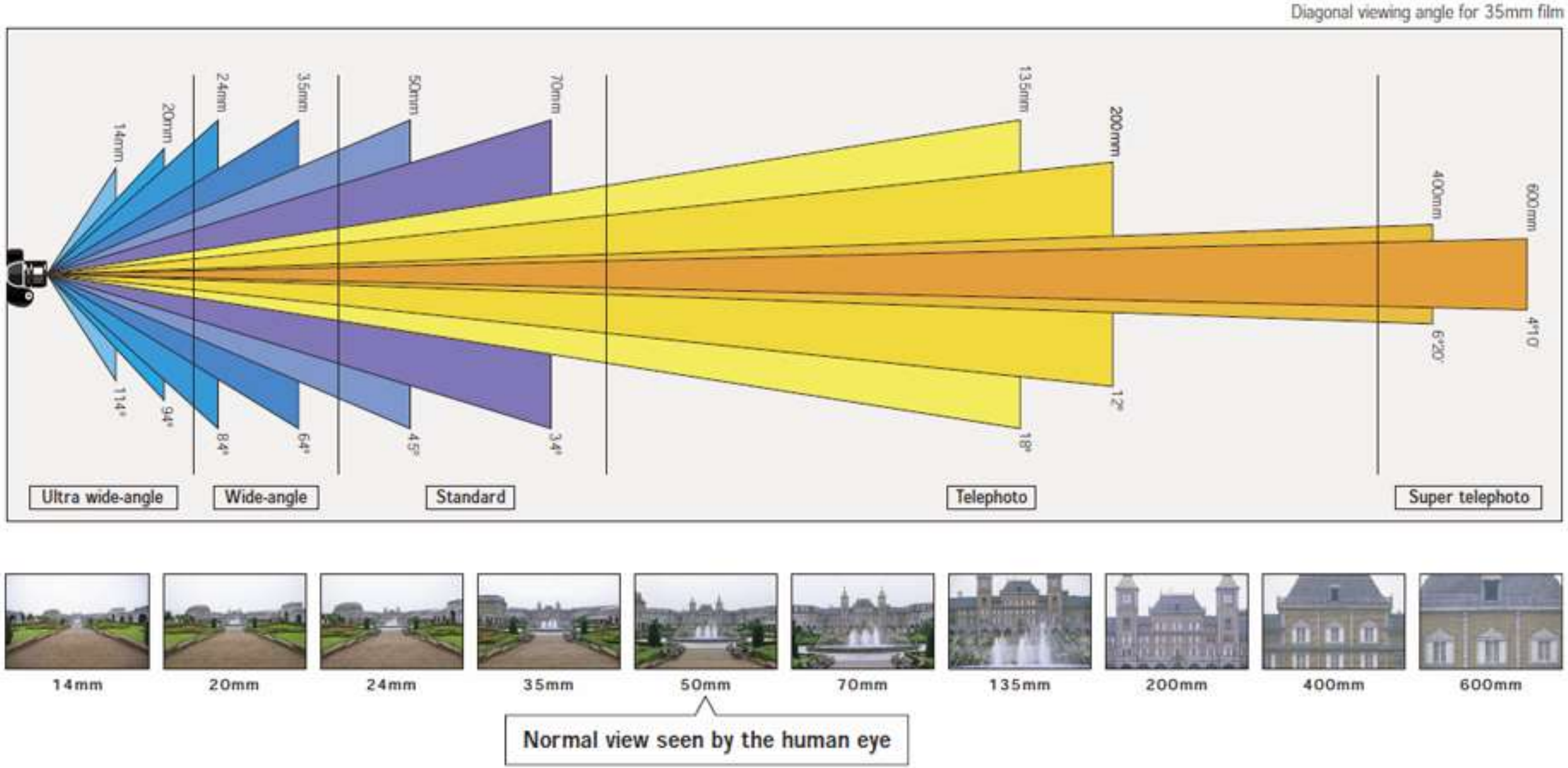
ccd size



$$y_{img} = f_m \frac{h_{img}}{h_{ccd}} \frac{Y}{Z}$$

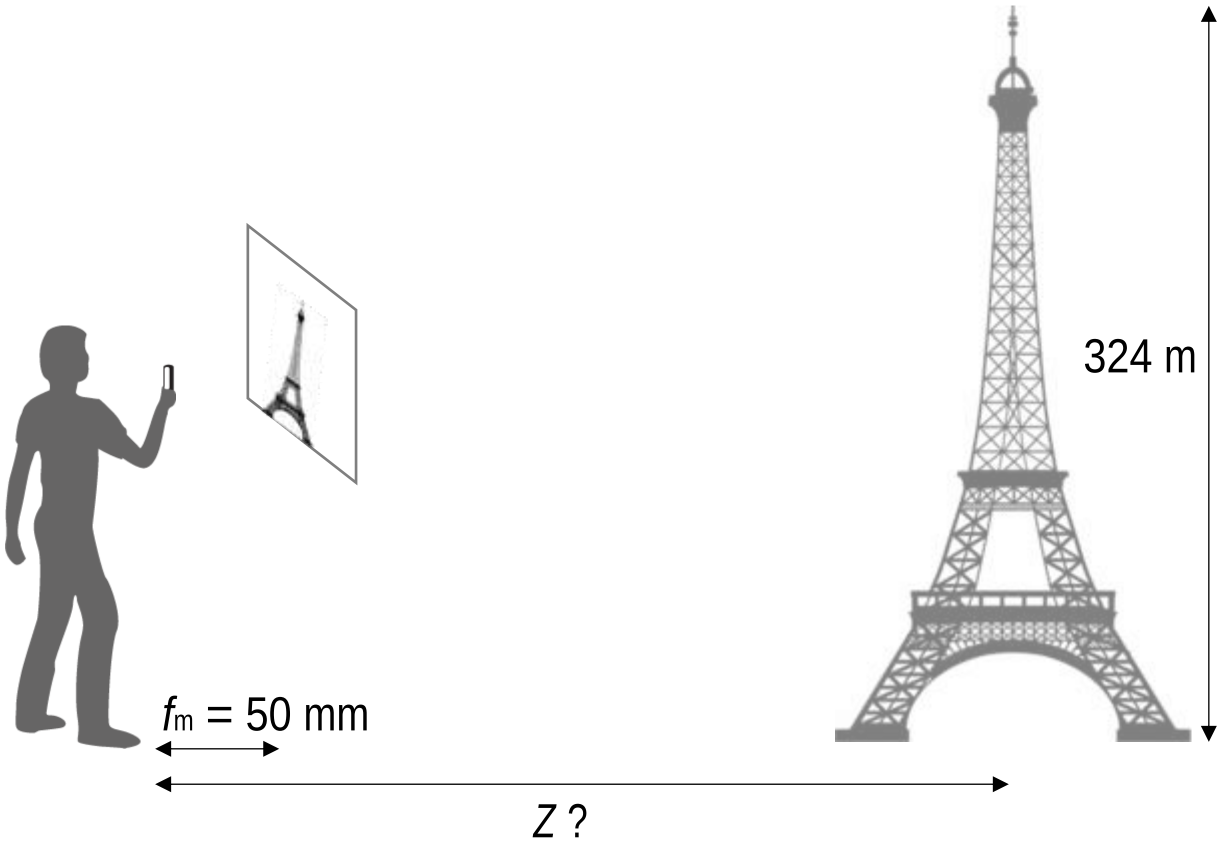
$$960 = f_m \frac{1280}{0.0218} \frac{324}{1500} \rightarrow f_m = 0.0757\text{m}$$

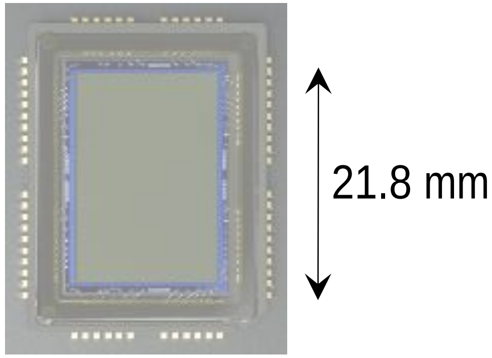
Focal Length



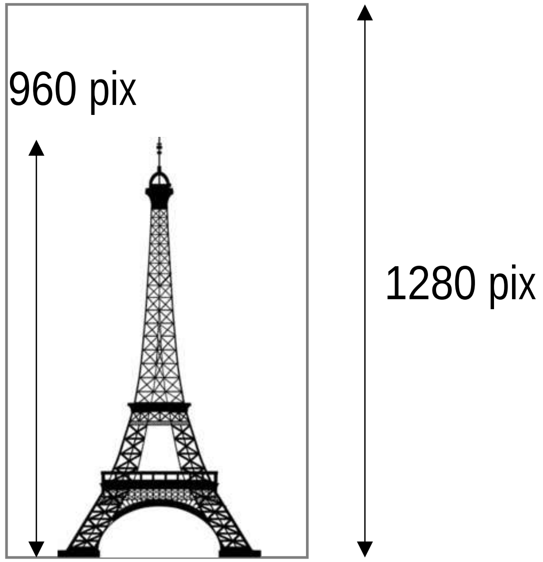
What Z to make the height of Eifel tower appear 960 pixel distance?

Exercise





ccd size

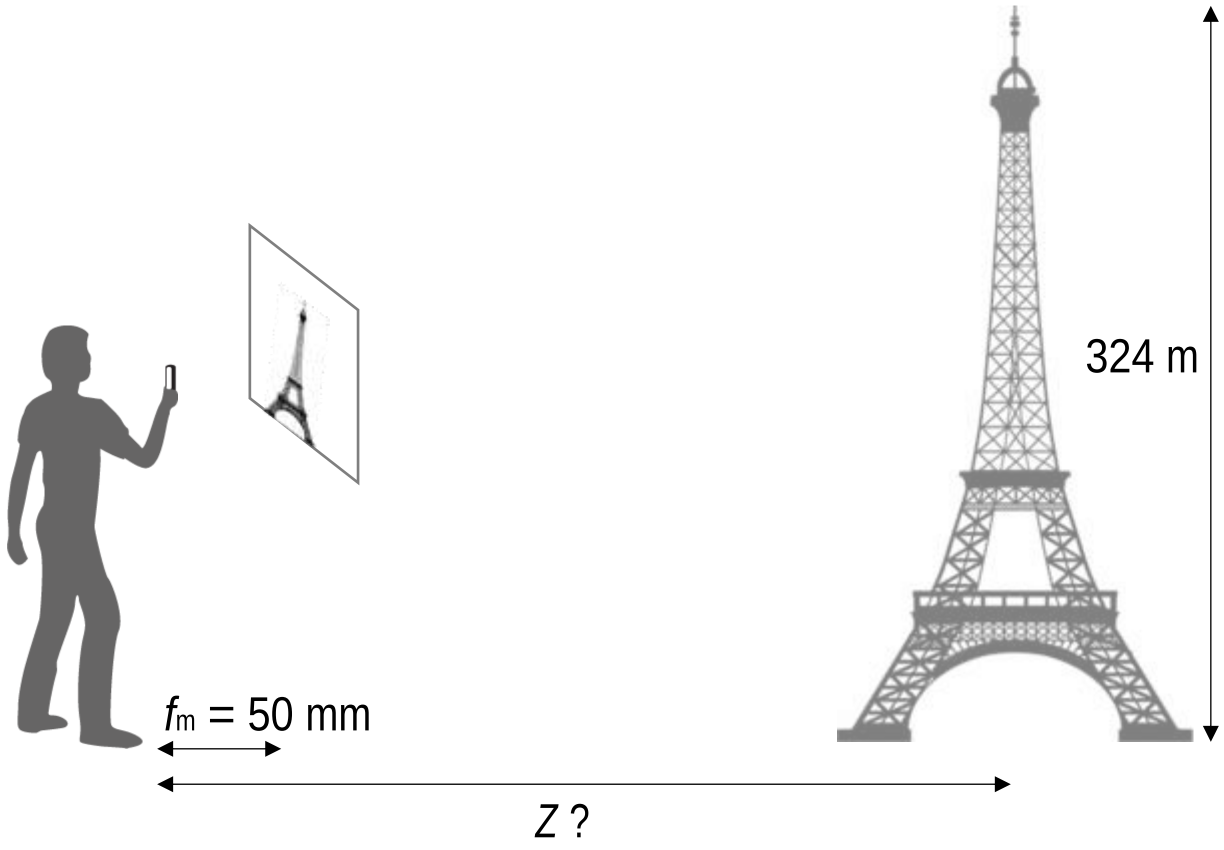


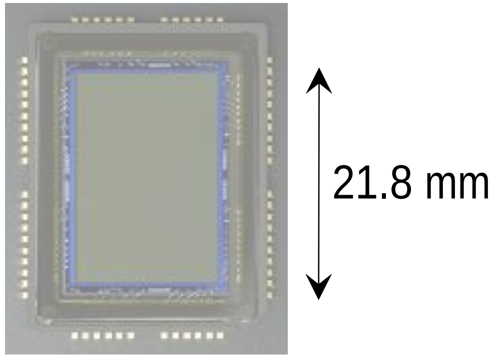
$$y_{img} = f_m \frac{h_{img}}{h_{ccd}} \frac{Y}{Z}$$

Do I need to move backward or forward?

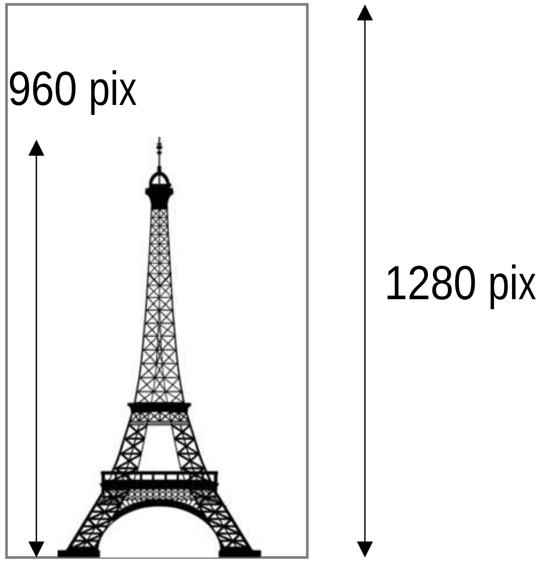
Exercise

What *Z* to make the height of Eifel tower appear 960 pixel distance?





ccd size



$$y_{img} = f_m \frac{h_{img}}{h_{ccd}} \frac{Y}{Z}$$

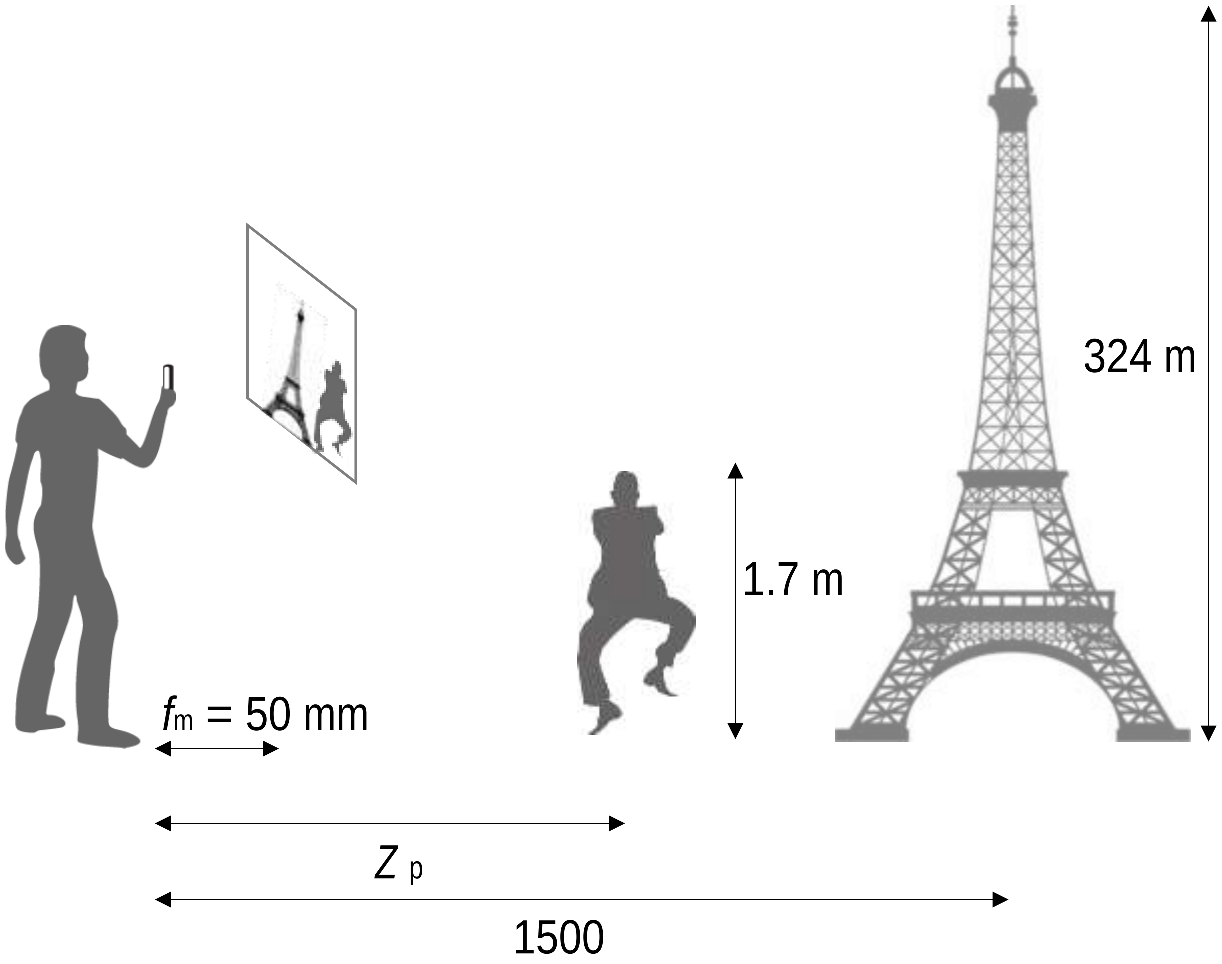
$$960 = 0.05 \frac{1280}{0.0218} \frac{324}{Z} \rightarrow Z = 990.826\text{m}$$

Do I need to move backward or forward?

Forward

Exercise

What Z_p to make the height of Eifel tower appear twice of the person?



Where Was I?

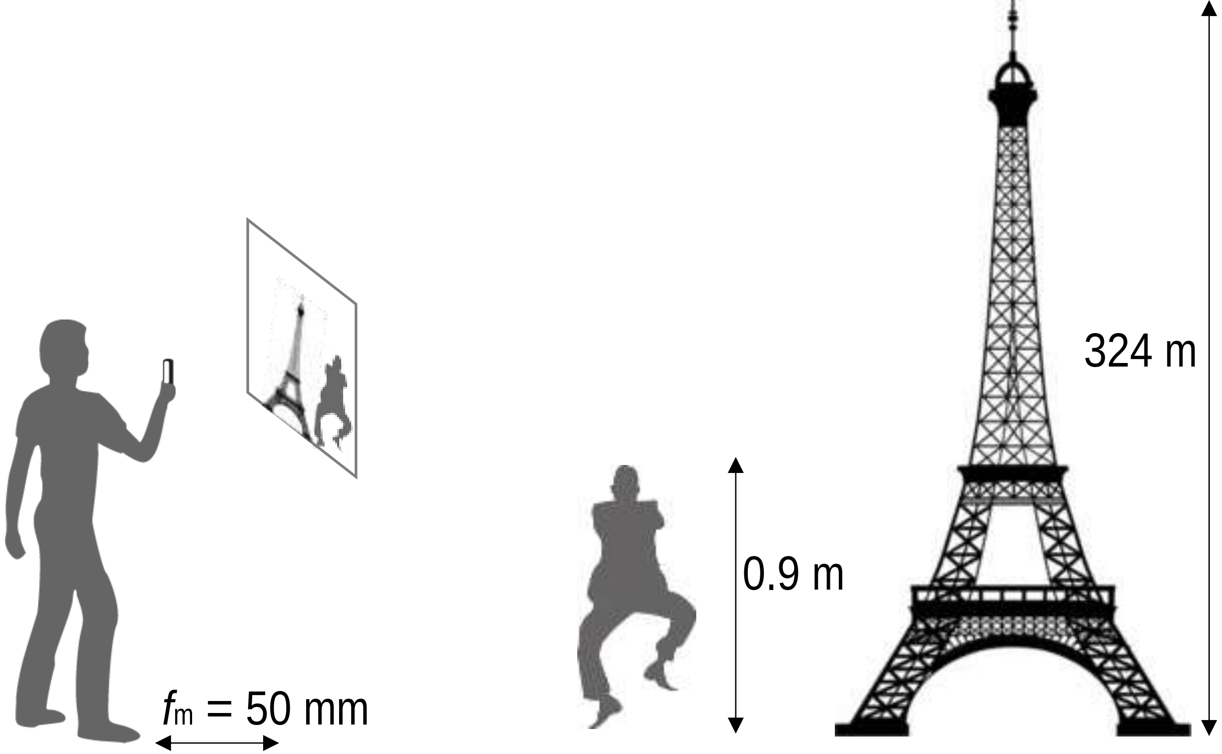
Circa 1984

Where Was I?

Circa 1984

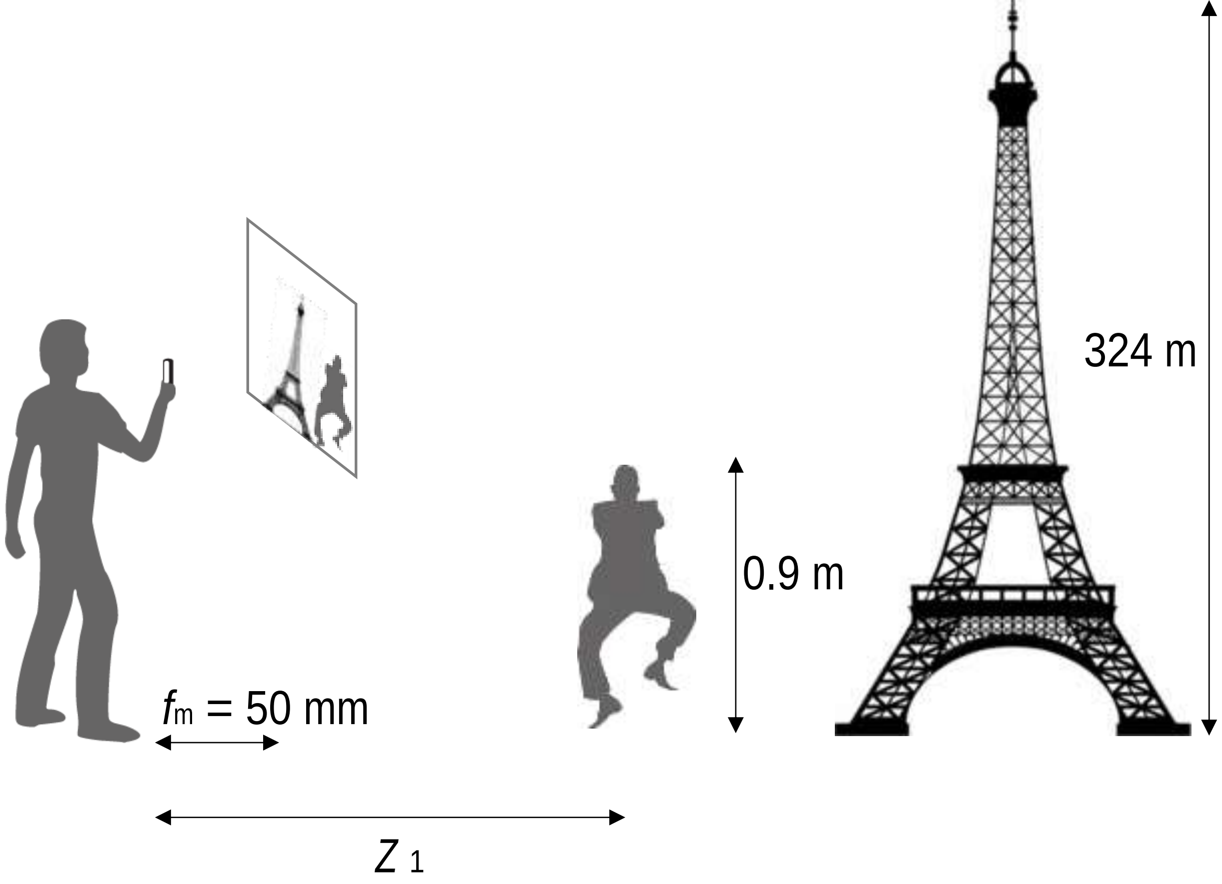
Where Was I?

Circa 1984



Where Was I?

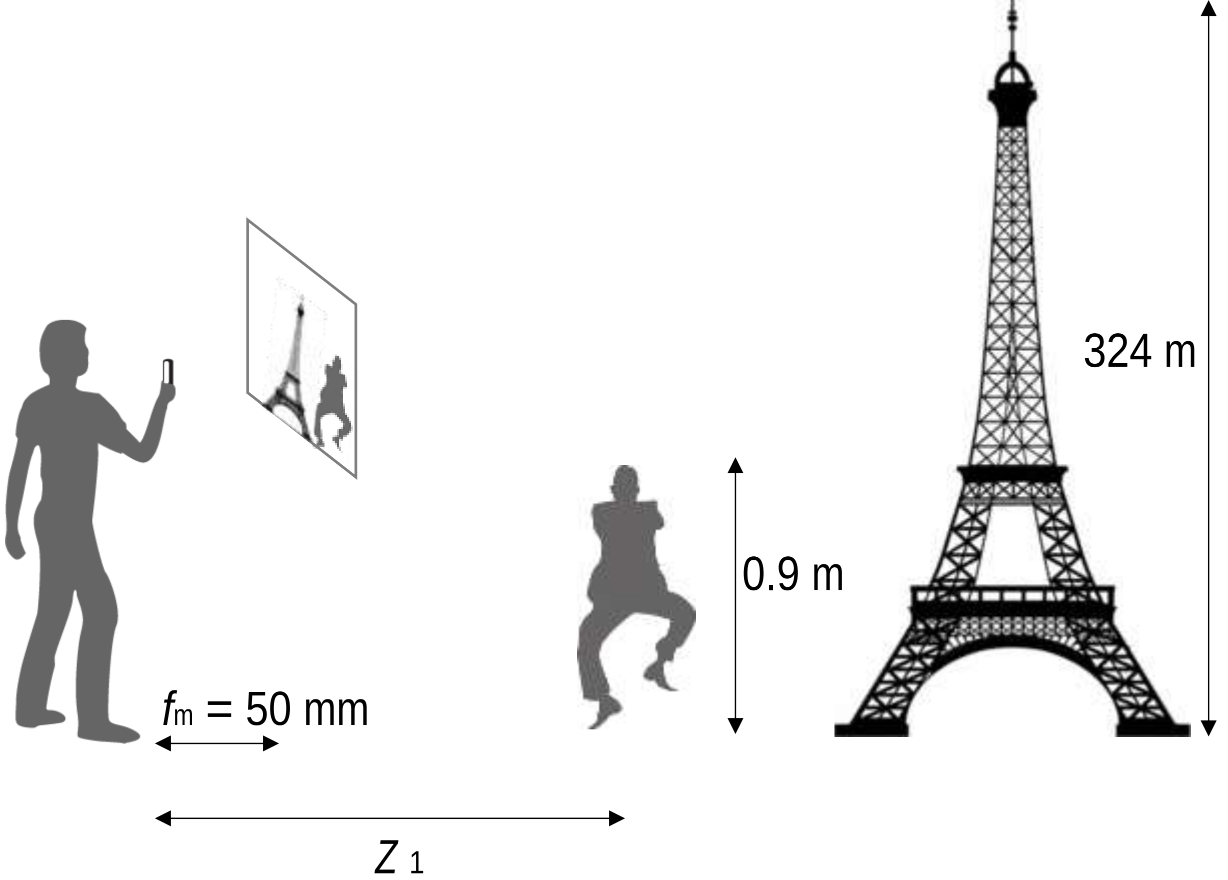
Circa 1984



$$y_1 = f_m \frac{h_{\text{img}}}{h_{\text{ccd}}} \frac{Y_1}{Z_1}.$$

Where Was I?

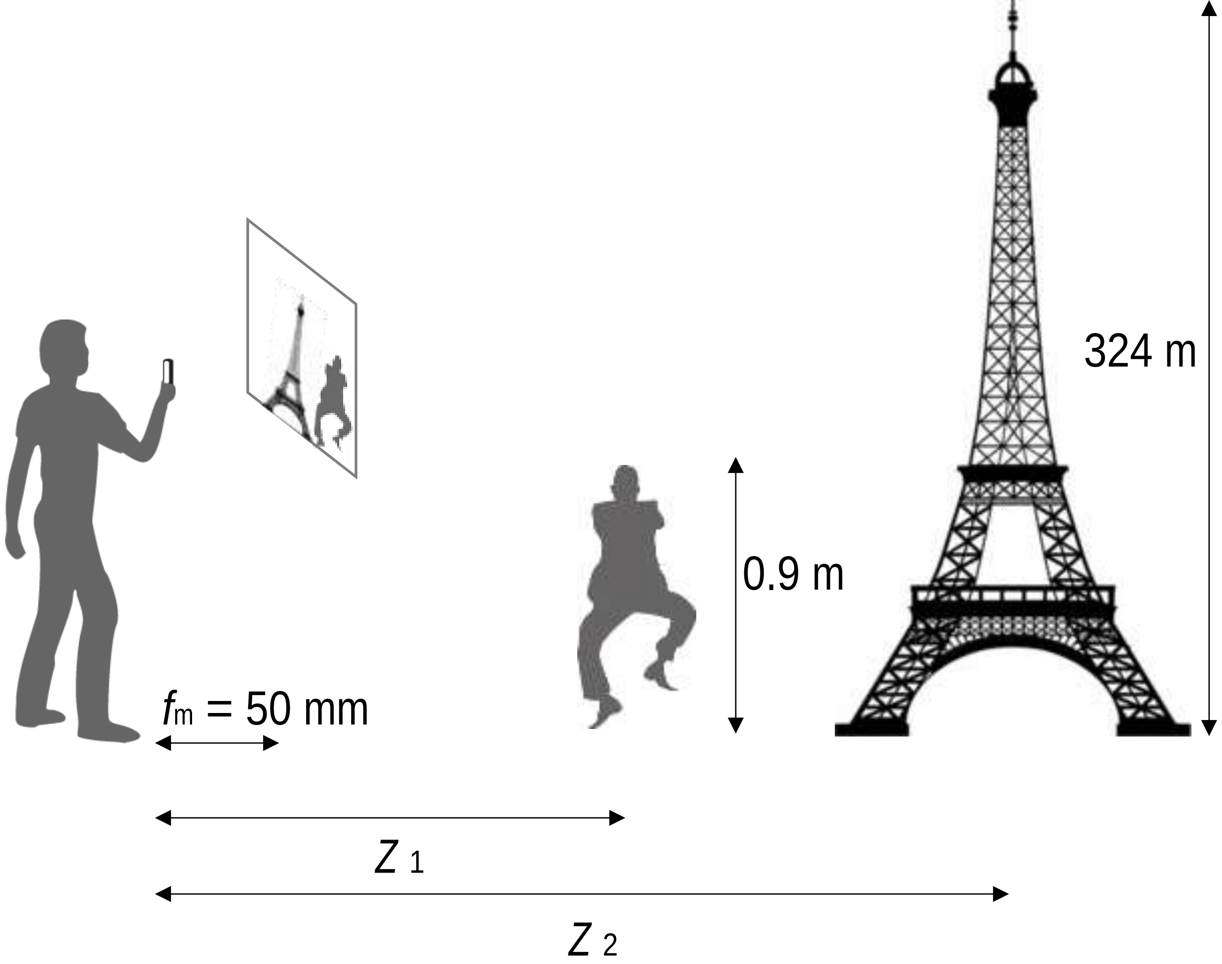
Circa 1984



$$y_1 = f_m \frac{h_{img}}{h_{ccd}} \frac{Y_1}{Z_1} \rightarrow Z_1 = f_m \frac{h_{img}}{h_{ccd}} \frac{Y_1}{y_1} = 0.05 \frac{1280}{0.0218} \frac{0.9}{250} = 8.03\text{m}$$

Where Was I?

Circa 1984



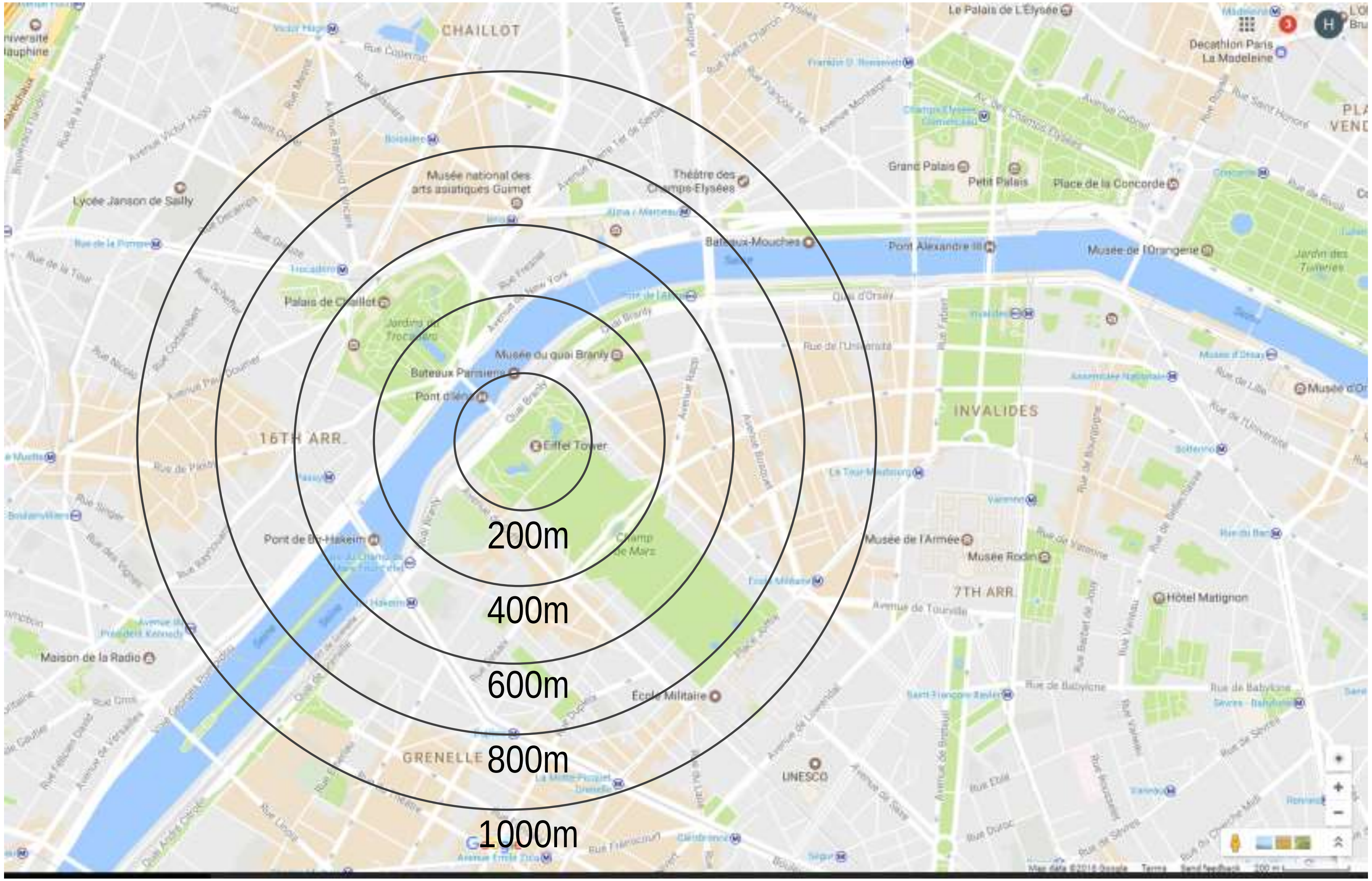
$$y_1 = f_m \frac{h_{img}}{h_{ccd}} \frac{Y_1}{Z_1} \rightarrow Z_1 = f_m \frac{h_{img}}{h_{ccd}} \frac{Y_1}{y_1} = 0.05 \frac{1280}{0.0218} \frac{0.9}{250} = 8.03\text{m}$$

$$y_2 = f_m \frac{h_{img}}{h_{ccd}} \frac{Y_2}{Z_2} \rightarrow Z_2 = f_m \frac{h_{img}}{h_{ccd}} \frac{Y_2}{y_2} = 0.05 \frac{1280}{0.0218} \frac{324}{670} = 1079\text{m}$$

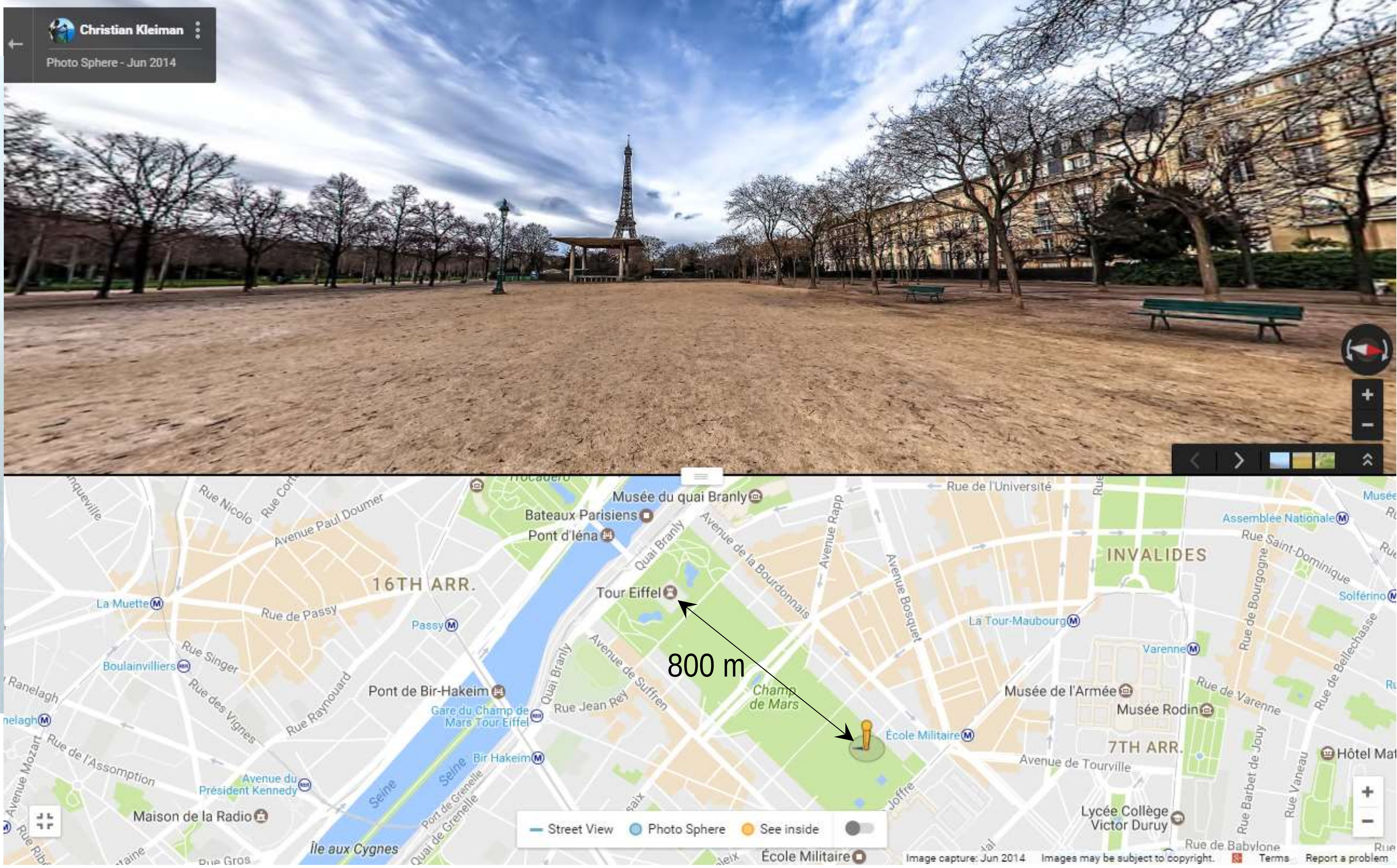
Where Was I?

$$y_2 = f\frac{Y_2}{Z_2} = f_m\frac{h_{img}}{h_{ccd}}\frac{Y_2}{Z_2} \rightarrow Z_2 = f_m\frac{h_{img}}{h_{ccd}}\frac{Y_2}{y_2} = 0.05\frac{1280}{0.0218}\frac{324}{670} = 1079\text{m}$$

Circa 1984



Where Was I?


Christian Kleiman - Goog
https://www.google.com/maps/@48.8543756,2.302317,3a,75y,263.24h,97.25t/data=!3m11!1e1!3m9!1s-DoiSGv8hd-8%2FU5IYkvKzStI%2FAAAAAAAADeA%2FoVn2jx5rZboTCLUVLc6m
Bookmarks
Google Calendar
00 Writing - Google
My Drive - Google Dr
ToDoEveryday - Goog
Research Idea - Goog
slack
UMN
funding
Other bookmarks
Christian Kleiman
Photo Sphere - Jun 2014
Musée du quai Branly
Bateaux Parisiens
Pont d'Iéna
Tour Eiffel
800 m
Champ de Mars
École Militaire
16TH ARR.
INVALIDES
7TH ARR.
La Tour-Maubourg
Musée de l'Armée
Musée Rodin
Pont de Bir-Hakeim
Gare du Champ de Mars Tour Eiffel
Maison de la Radio
Île aux Cygnes
Street View
Photo Sphere
See inside
Image capture: Jun 2014
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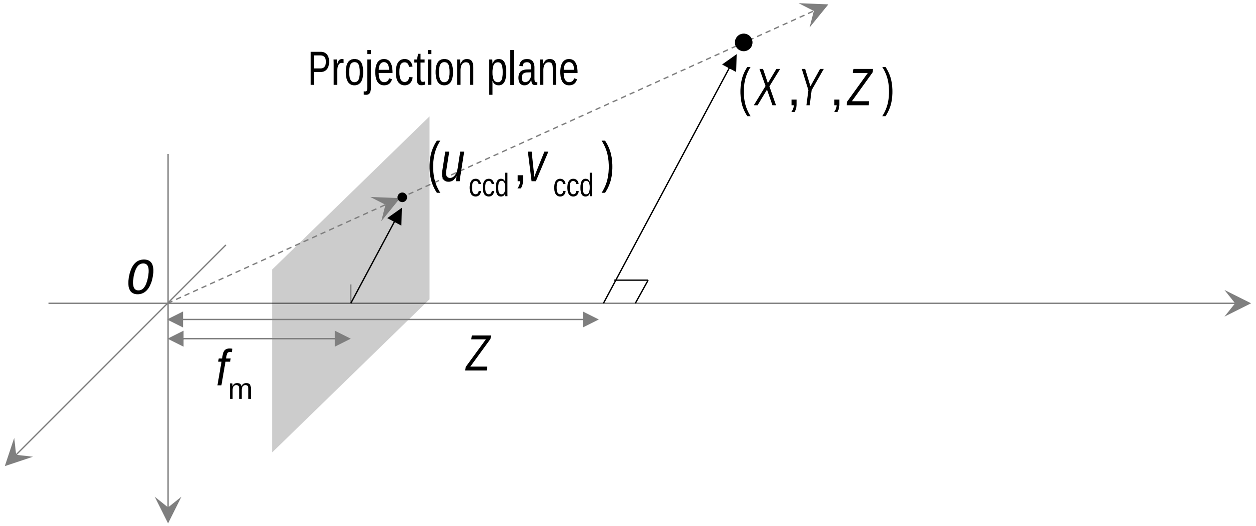
3D Point Projection (Pixel Space)

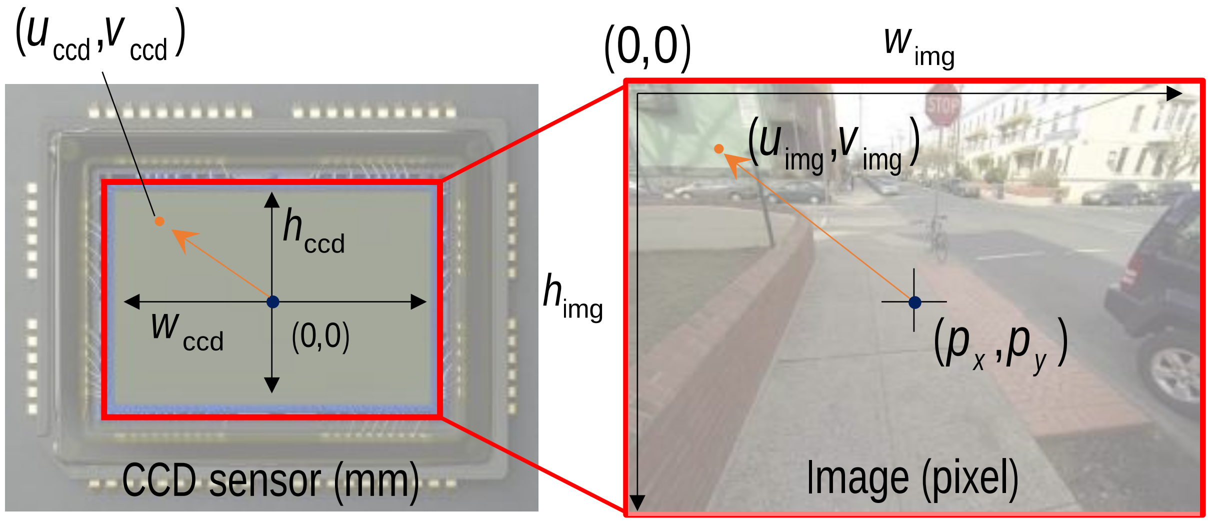


$$(u_{ccd}, v_{ccd}) = (f_m \frac{X}{Z}, f_m \frac{Y}{Z})$$: Metric projection

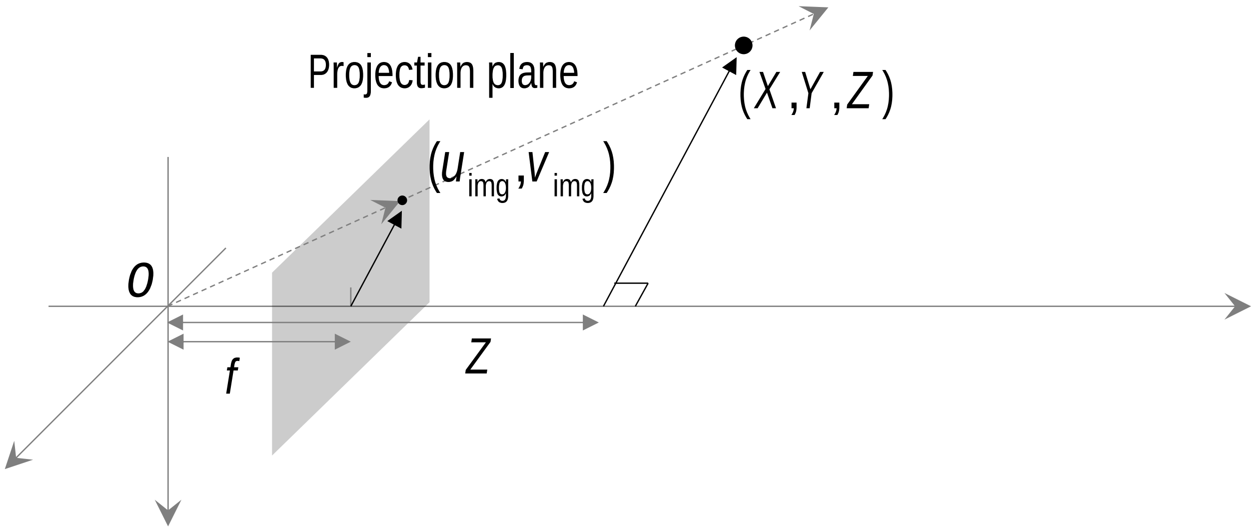
Pixel projection

$$\rightarrow u_{img} = u_{ccd} \frac{w_{img}}{w_{ccd}} + p_x = f_m \frac{w_{img}}{w_{ccd}} \frac{X}{Z} + p_x$$

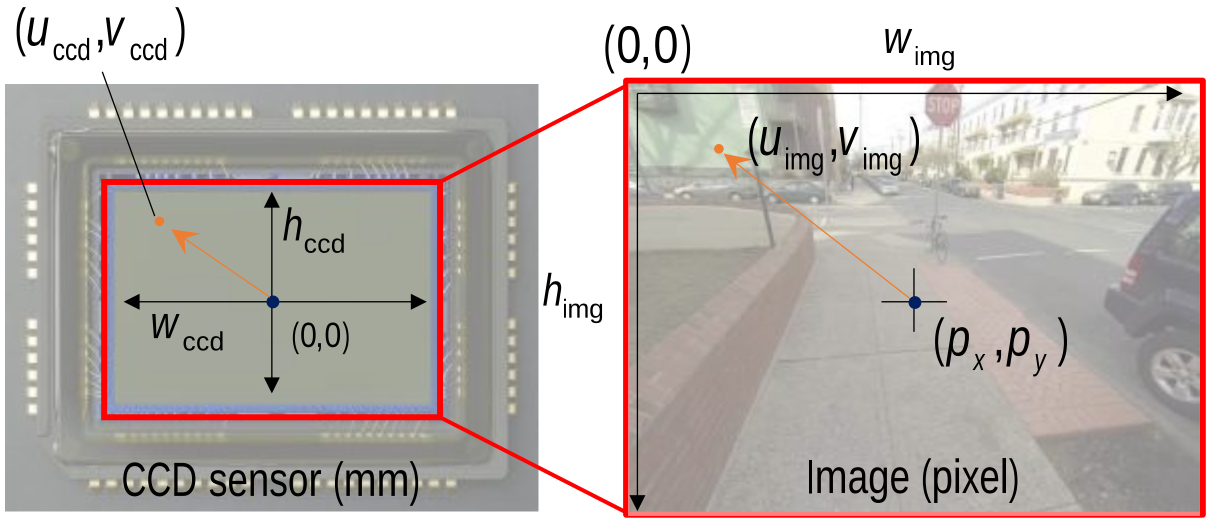
$$v_{img} = v_{ccd} \frac{h_{img}}{h_{ccd}} + p_y = f_m \frac{h_{img}}{h_{ccd}} \frac{Y}{Z} + p_y$$



3D Point Projection (Pixel Space)



$$(u_{ccd}, v_{ccd}) = (f_m \frac{X}{Z}, f_m \frac{Y}{Z})$$: Metric projection



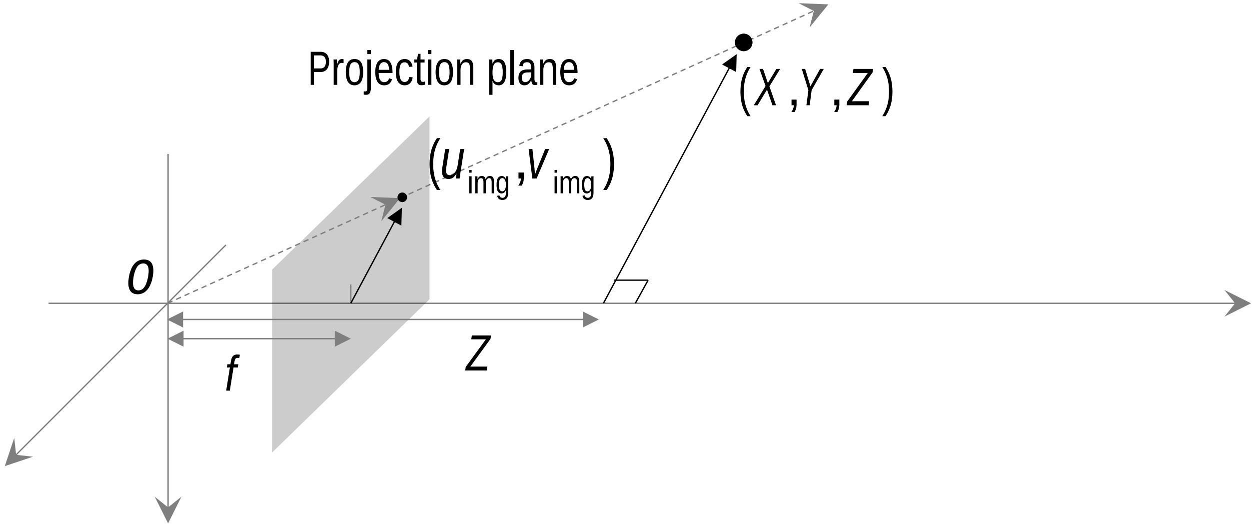
Pixel projection

$$\rightarrow u_{img} = u_{ccd} \frac{w_{img}}{w_{ccd}} + p_x = f_m \frac{w_{img}}{w_{ccd}} \frac{X}{Z} + p_x$$

$$v_{img} = v_{ccd} \frac{h_{img}}{h_{ccd}} + p_y = f_m \frac{h_{img}}{h_{ccd}} \frac{Y}{Z} + p_y$$

Focal length in pixel

3D Point Projection (Pixel Space)



$$(u_{ccd}, v_{ccd}) = \left(f_m \frac{X}{Z}, f_m \frac{Y}{Z}\right)$$: Metric projection

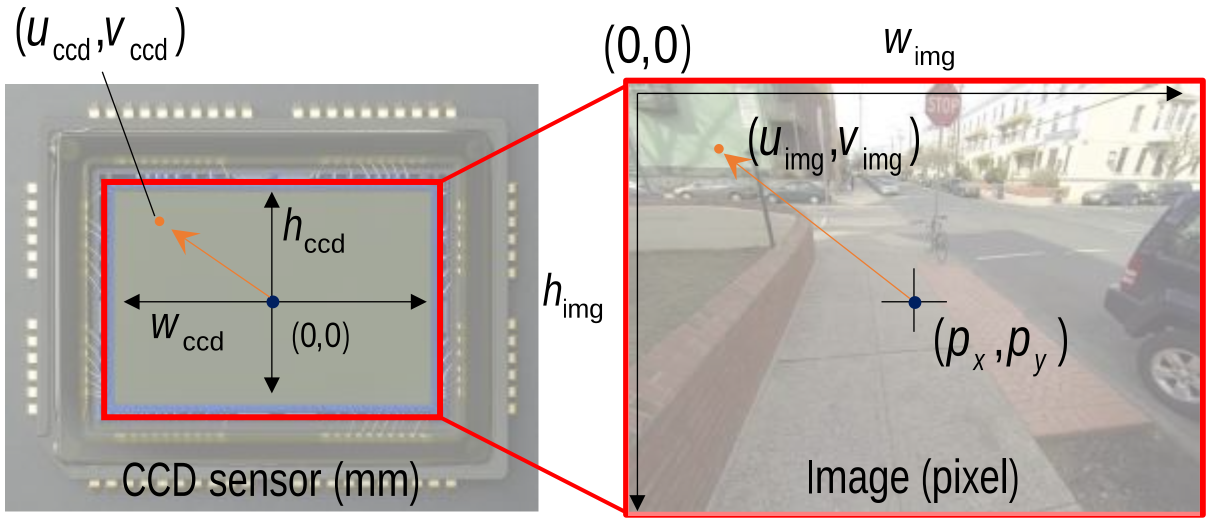
Pixel projection

$$\longrightarrow u_{img} = u_{ccd}\frac{w_{img}}{w_{ccd}} + p_x = f_x \frac{X}{Z} + p_x$$

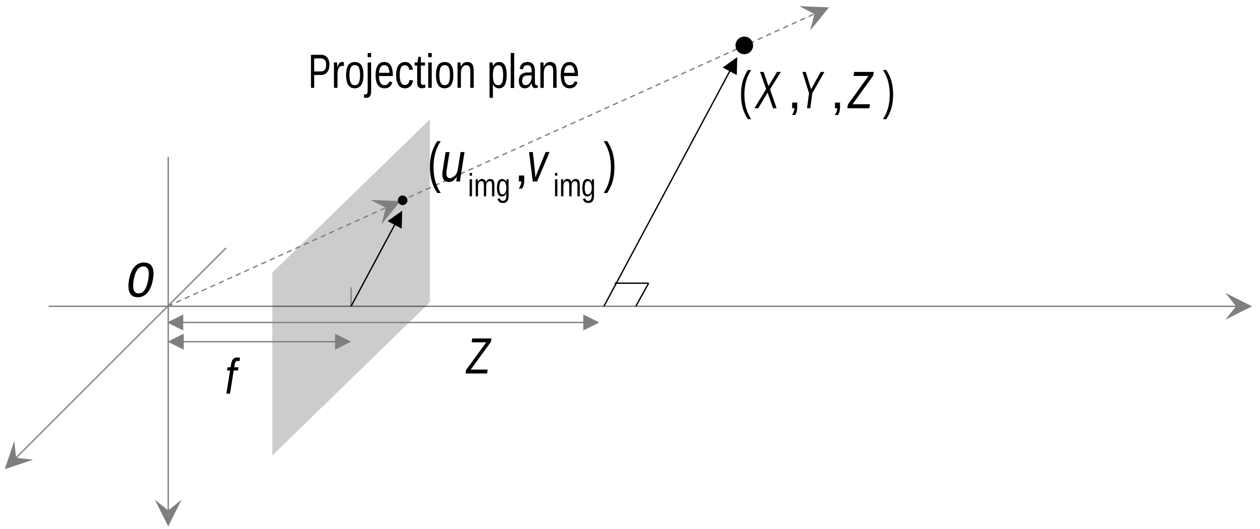
$$v_{img} = v_{ccd}\frac{h_{img}}{h_{ccd}} + p_y = f_y \frac{Y}{Z} + p_y$$

Focal length in pixel

where $f_x = f_m \frac{w_{img}}{w_{ccd}}$ $\quad f_y = f_m \frac{h_{img}}{h_{ccd}}$



3D Point Projection (Pixel Space)



$$(u_{ccd}, v_{ccd}) = (f_m \frac{X}{Z}, f_m \frac{Y}{Z})$$: Metric projection

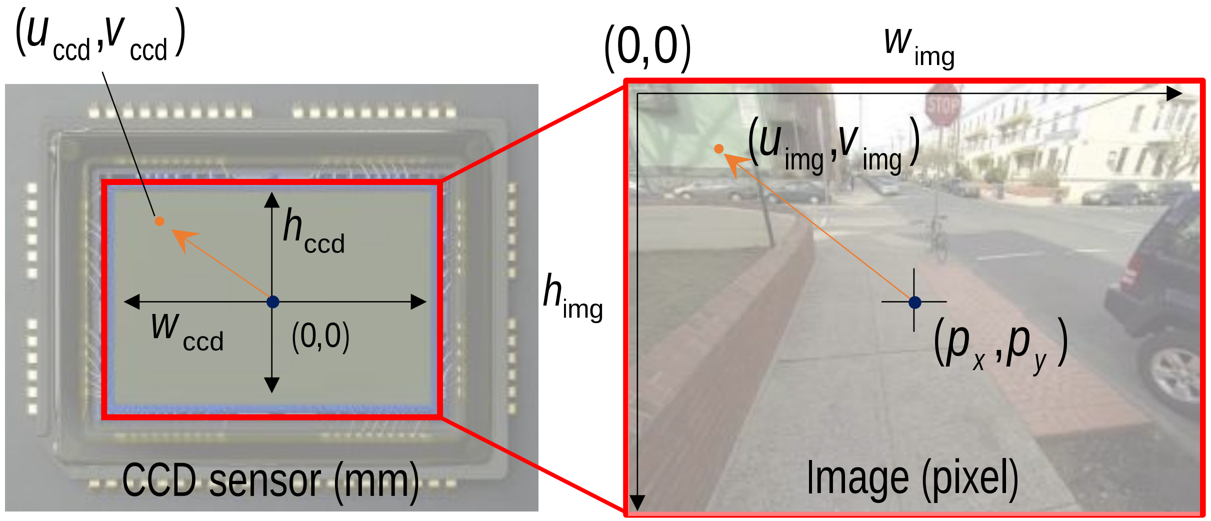
Pixel projection

$$\longrightarrow u_{img} = u_{ccd} \frac{w_{img}}{w_{ccd}} + p_x = f \frac{X}{Z} + p_x$$

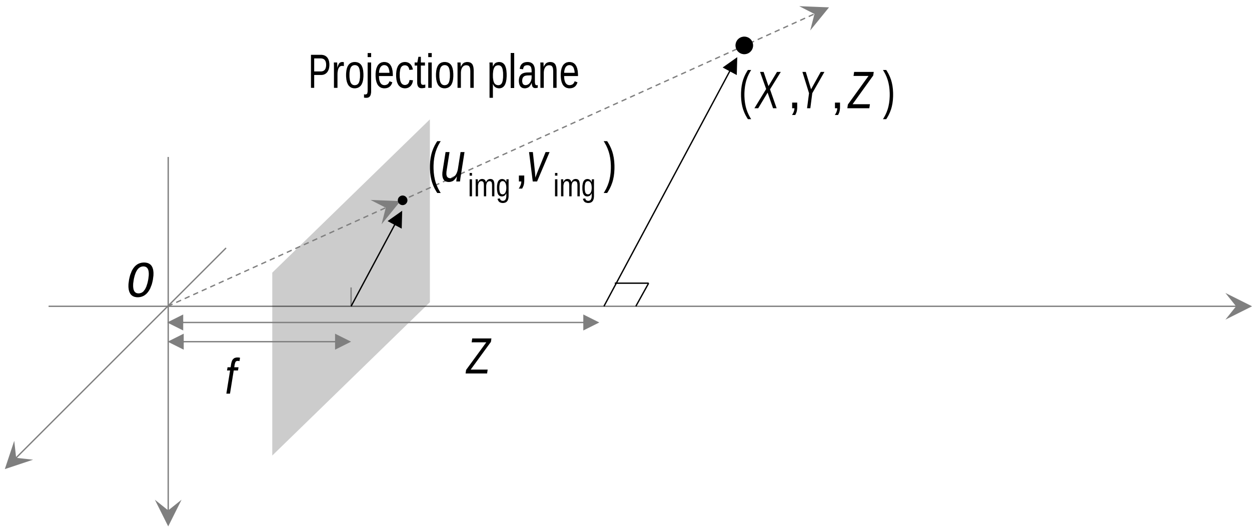
$$v_{img} = v_{ccd} \frac{h_{img}}{h_{ccd}} + p_y = f \frac{Y}{Z} + p_y$$

Focal length in pixel

$$\text{where } f = f_m \frac{w_{img}}{w_{ccd}} = f_m \frac{h_{img}}{h_{ccd}} \quad \text{if } \frac{w_{img}}{w_{ccd}} = \frac{h_{img}}{h_{ccd}}$$

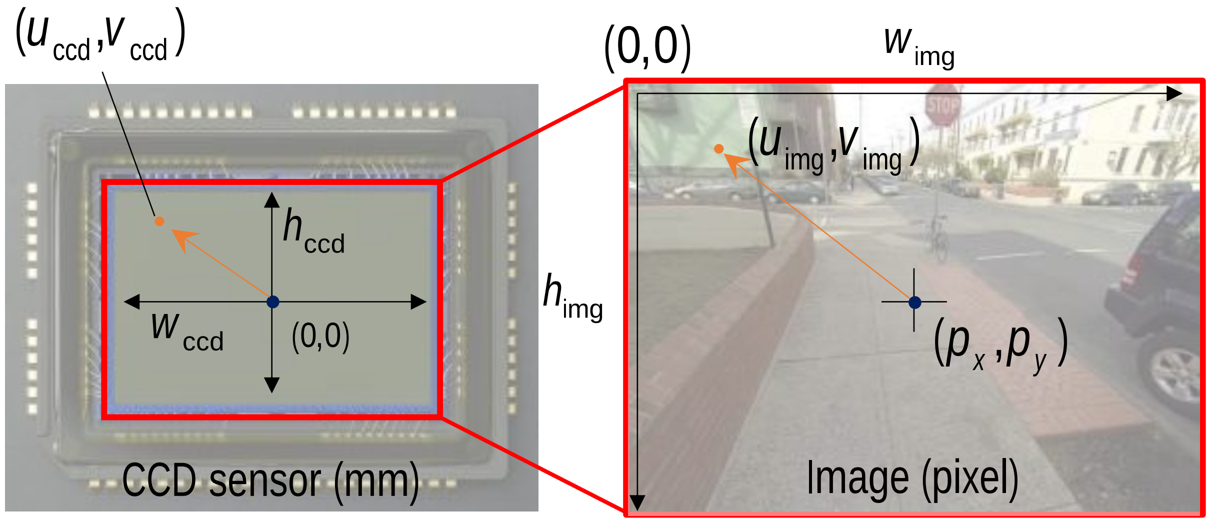


3D Point Projection (Pixel Space)

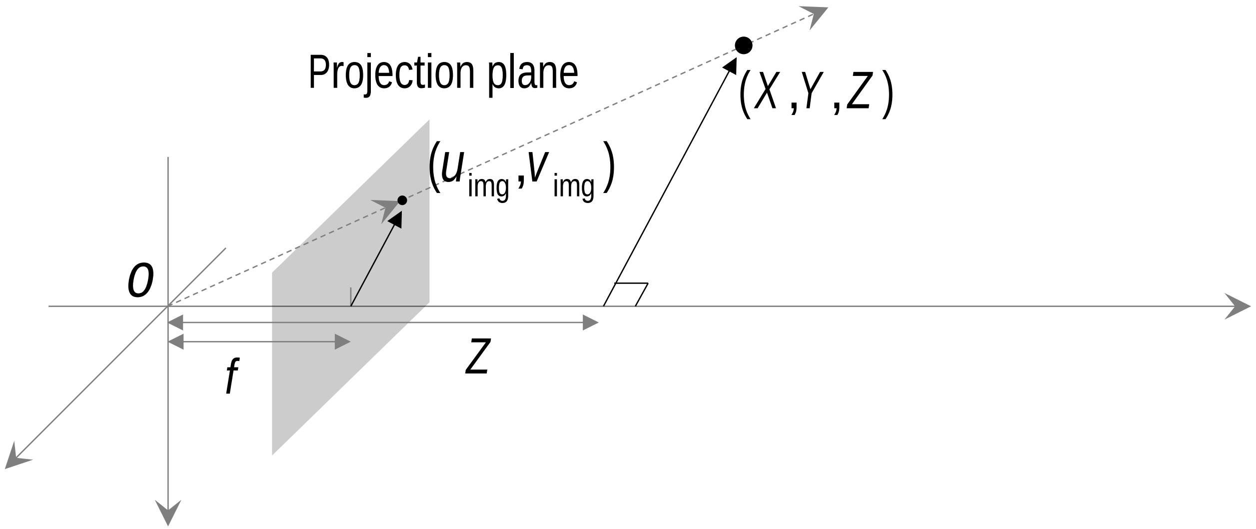


$$u_{img} = f\frac{X}{Z} + p_x$$

$$v_{img} = f\frac{Y}{Z} + p_y$$

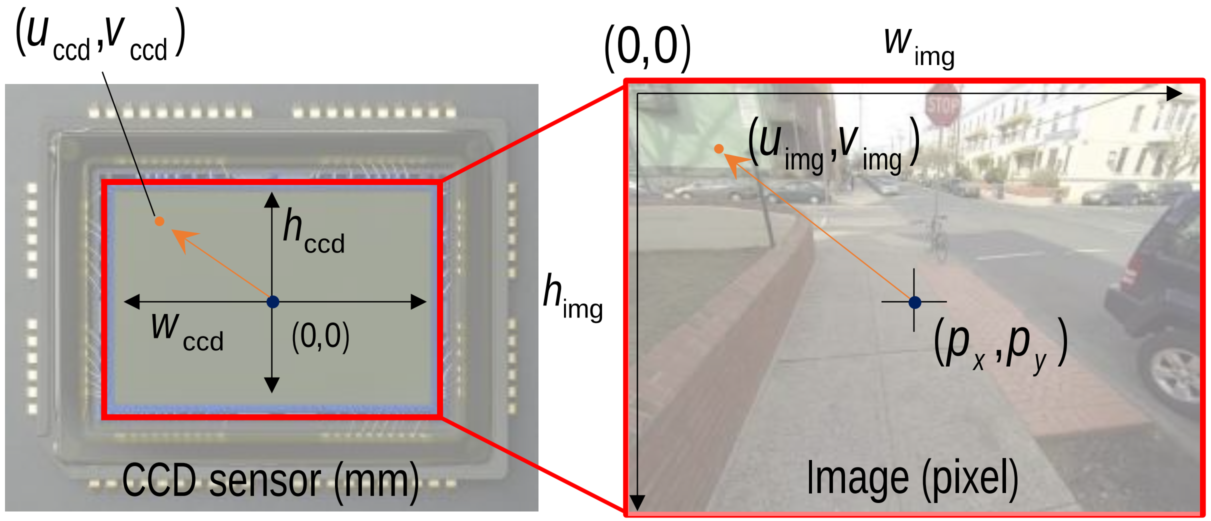


3D Point Projection (Pixel Space)

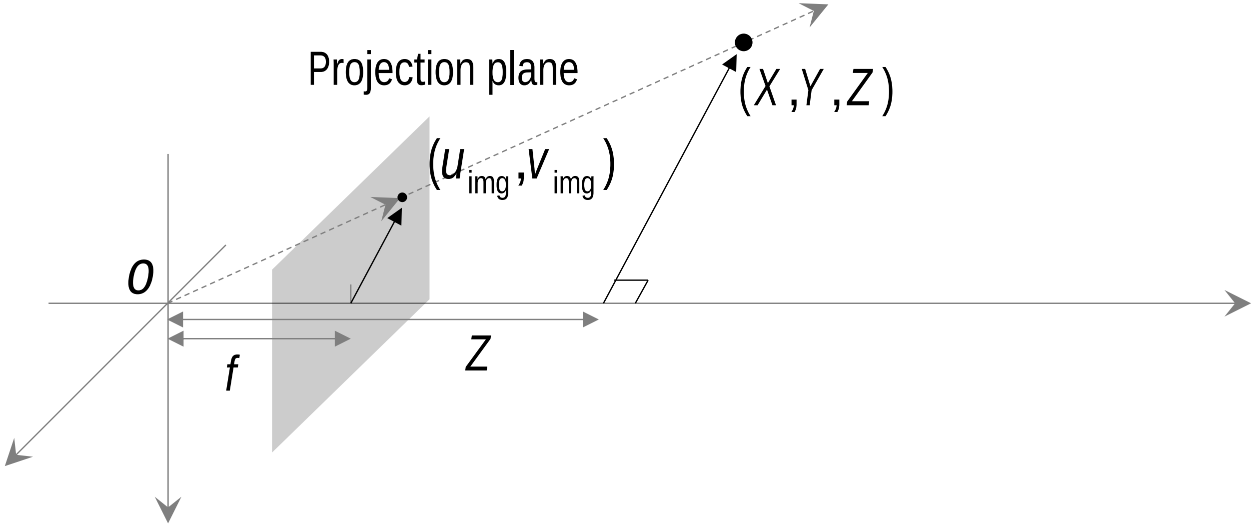


$$u_{img} = f\frac{X}{Z} + p_x \longrightarrow Zu_{img} = fX + p_x Z$$

$$v_{img} = f\frac{Y}{Z} + p_y \longrightarrow Zv_{img} = fY + p_y Z$$



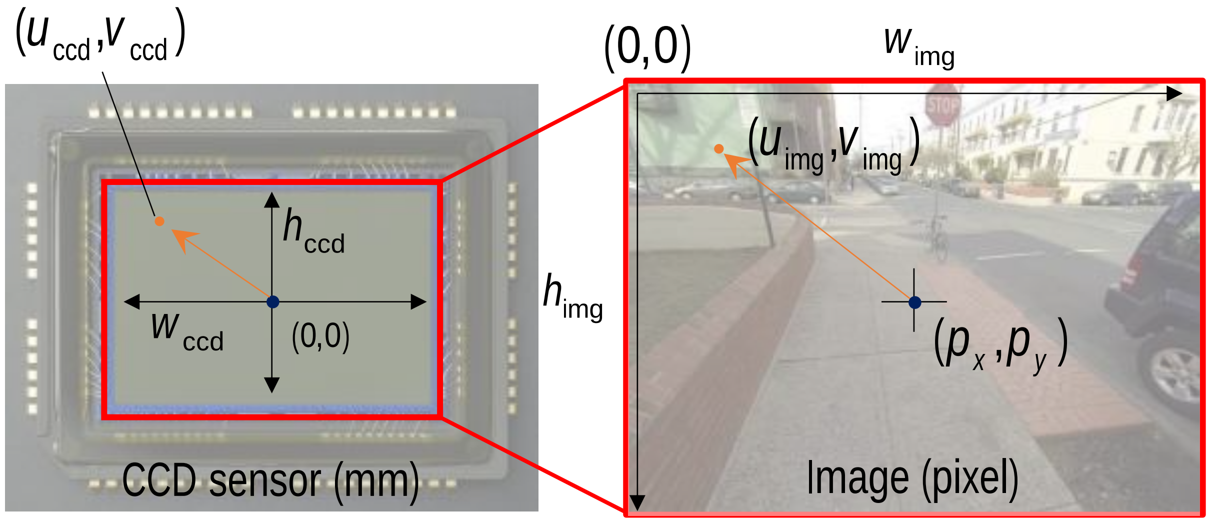
3D Point Projection (Pixel Space)



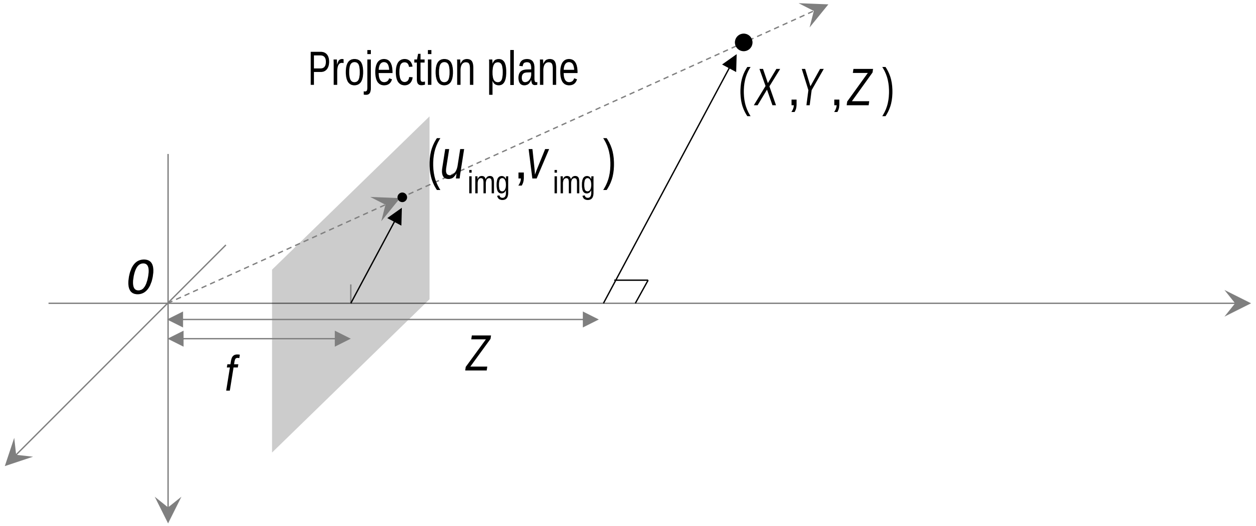
$$u_{img} = f\frac{X}{Z} + p_x \quad \longrightarrow \quad Zu_{img} = fX + p_x Z$$

$$v_{img} = f\frac{Y}{Z} + p_y \quad \longrightarrow \quad Zv_{img} = fY + p_y Z$$

$$Z\begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$



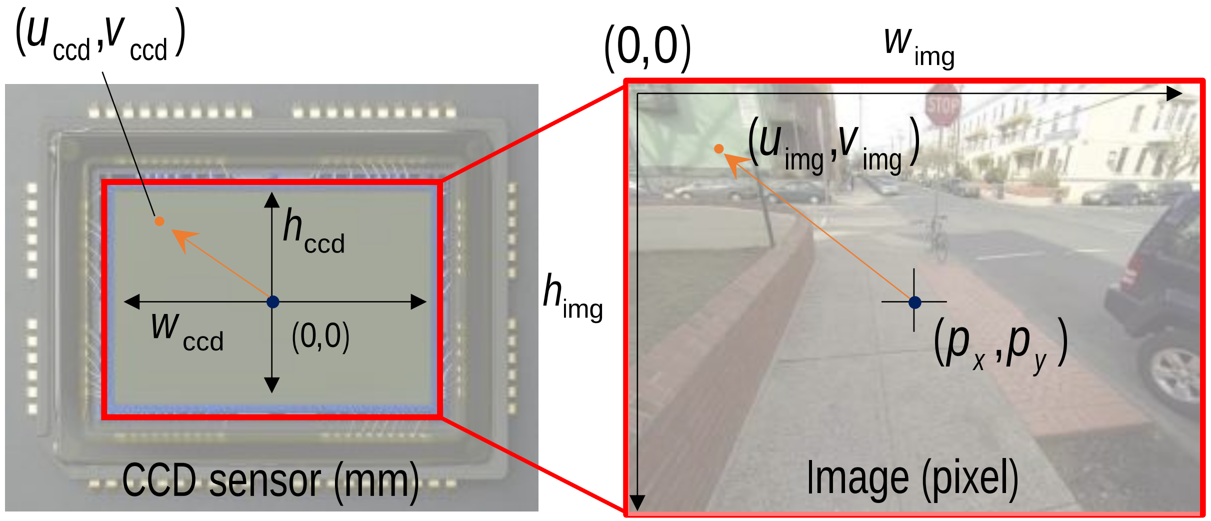
3D Point Projection (Pixel Space)



$$u_{img} = f\frac{X}{Z} + p_x \longrightarrow Zu_{img} = fX + p_x Z$$

$$v_{img} = f\frac{Y}{Z} + p_y \longrightarrow Zv_{img} = fY + p_y Z$$

$$\lambda \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$



Computer Graphics

$$u_{img} = f\frac{X}{Z} + p_x \longrightarrow Zu_{img} = fX + p_x Z$$

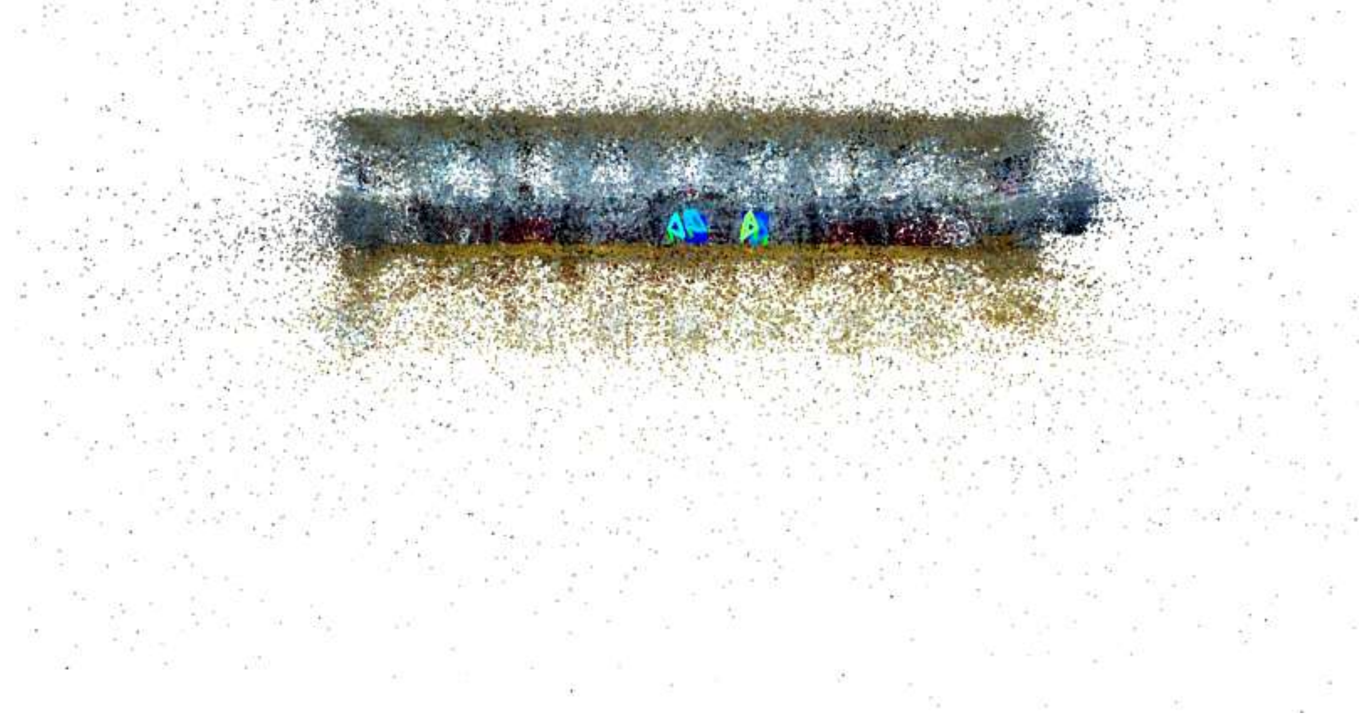
$$v_{img} = f\frac{Y}{Z} + p_y \longrightarrow Zv_{img} = fY + p_y Z$$

$$\lambda \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$\longleftarrow$

Graphics

Computer Vision = inv(Computer Graphics)



$$u_{\text{img}} = f\frac{X}{Z} + p_x \longrightarrow Zu_{\text{img}} = fX + p_x Z$$

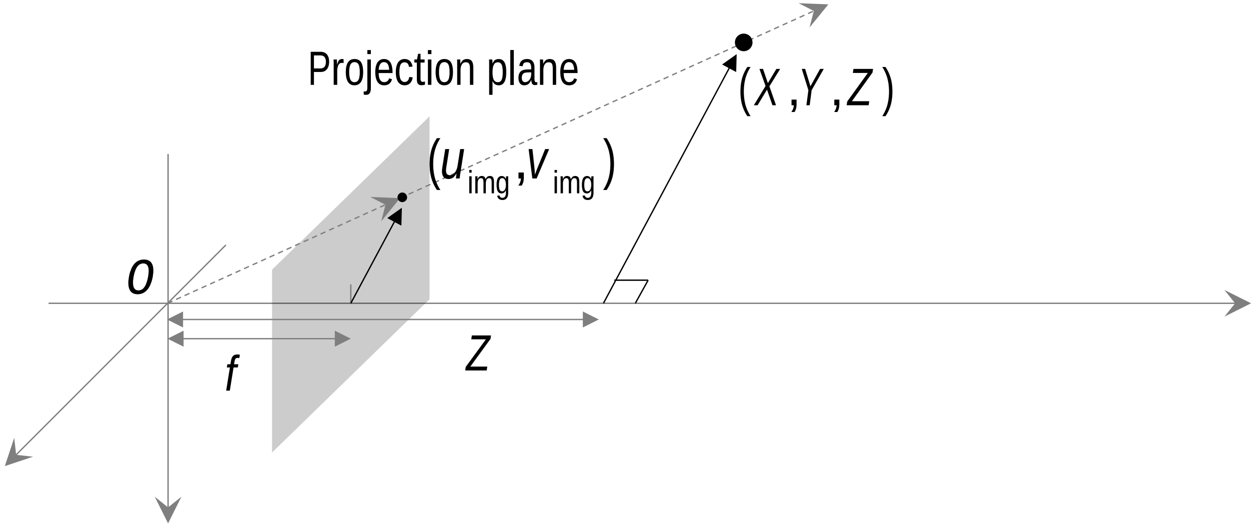
$$v_{\text{img}} = f\frac{Y}{Z} + p_y \longrightarrow Zv_{\text{img}} = fY + p_y Z$$

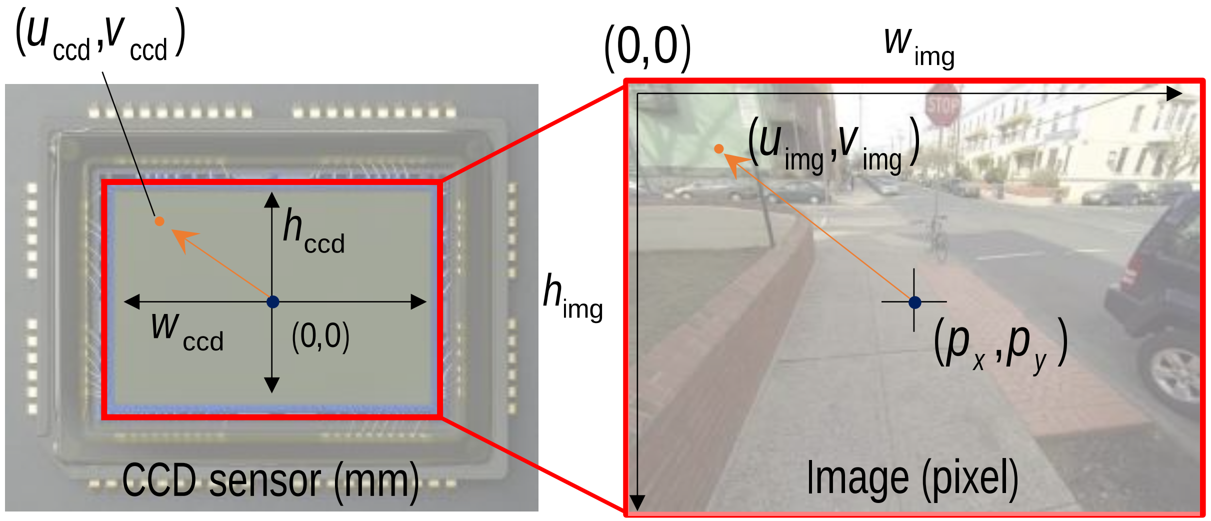
$$\lambda \begin{bmatrix} u_{\text{img}} \\ v_{\text{img}} \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

← Graphics

→ Vision

3D Point Projection (Pixel Space)





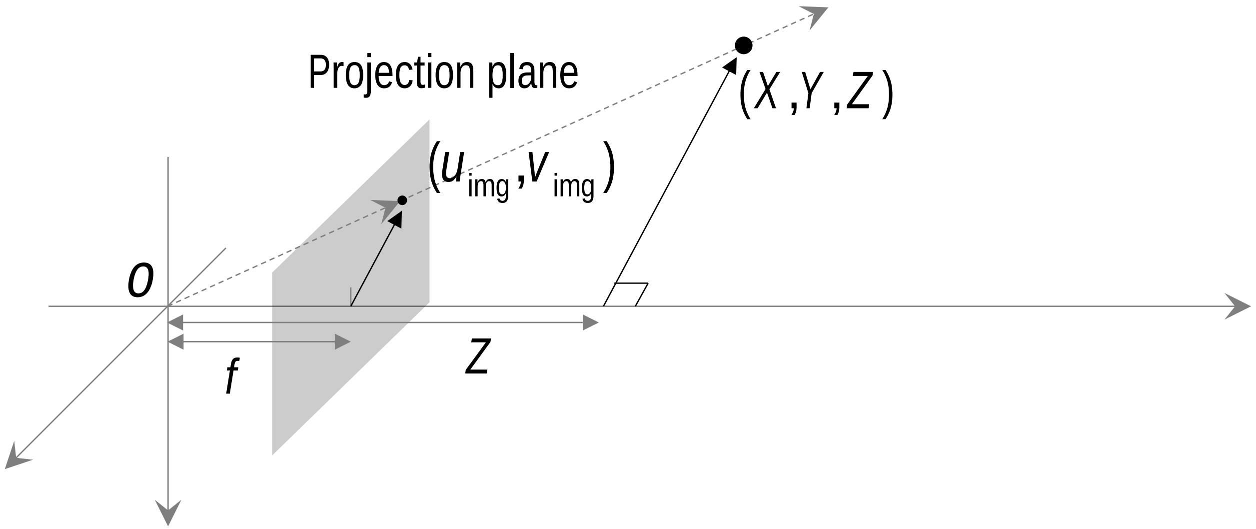
$$u_{img} = f\frac{X}{Z} + p_x \longrightarrow Zu_{img} = fX + p_x Z$$

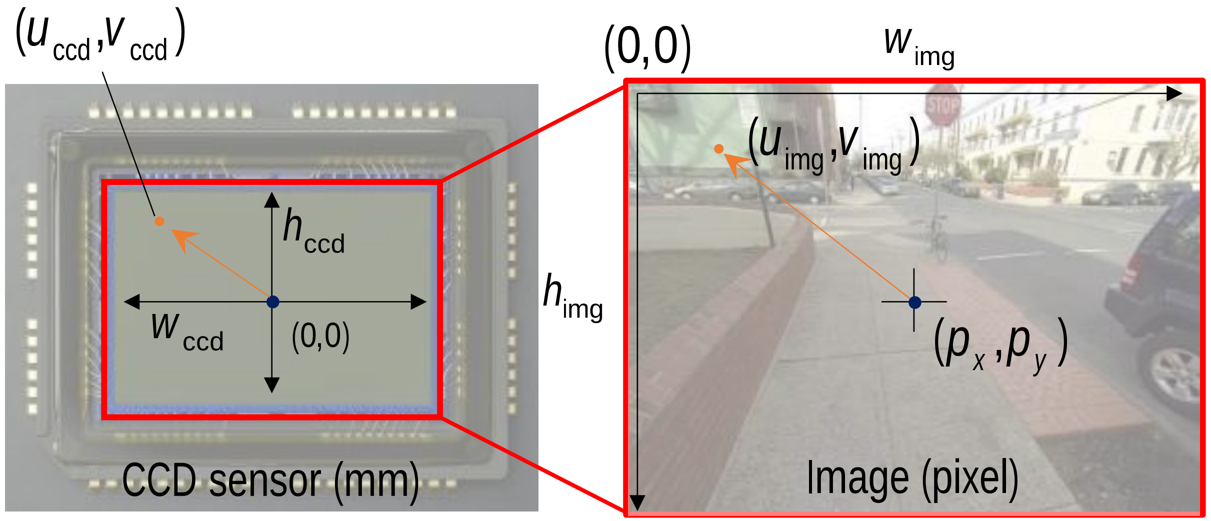
$$v_{img} = f\frac{Y}{Z} + p_y \longrightarrow Zv_{img} = fY + p_y Z$$

Pixel space — Metric space

$$\lambda \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

3D Point Projection (Pixel Space)



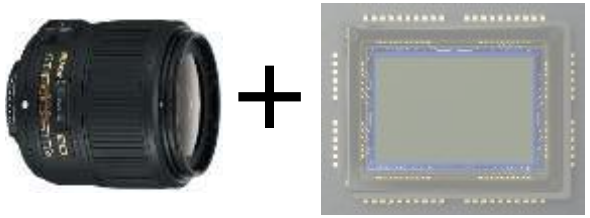


$$u_{img} = f\frac{X}{Z} + p_x \longrightarrow Zu_{img} = fX + p_x Z$$

$$v_{img} = f\frac{Y}{Z} + p_y \longrightarrow Zv_{img} = fY + p_y Z$$

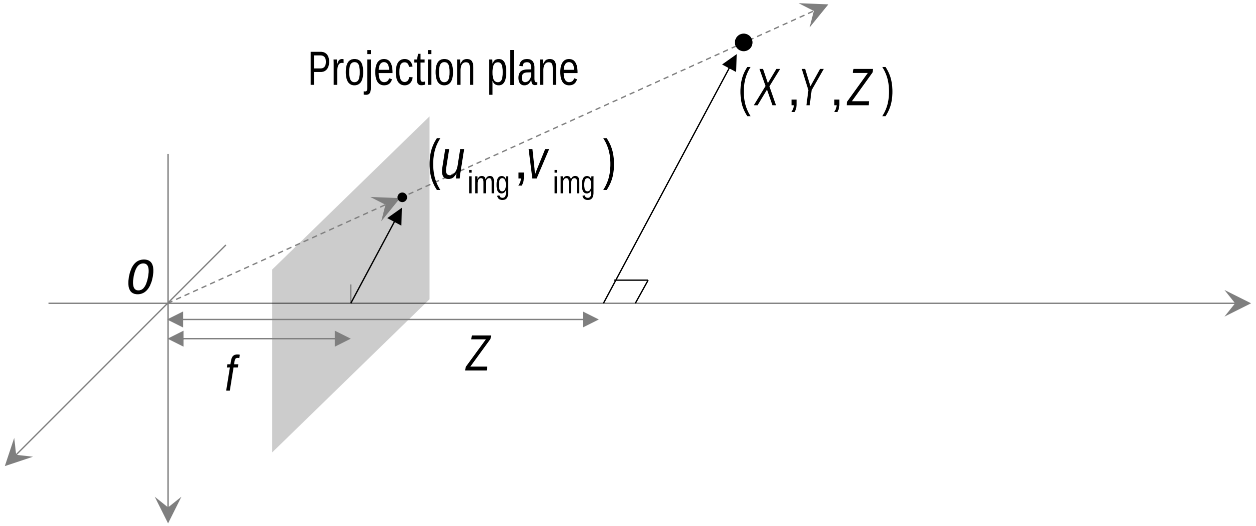
Pixel space Metric space

$$\lambda \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$



Camera intrinsic parameter
: metric space to pixel space

3D Point Projection (Pixel Space)

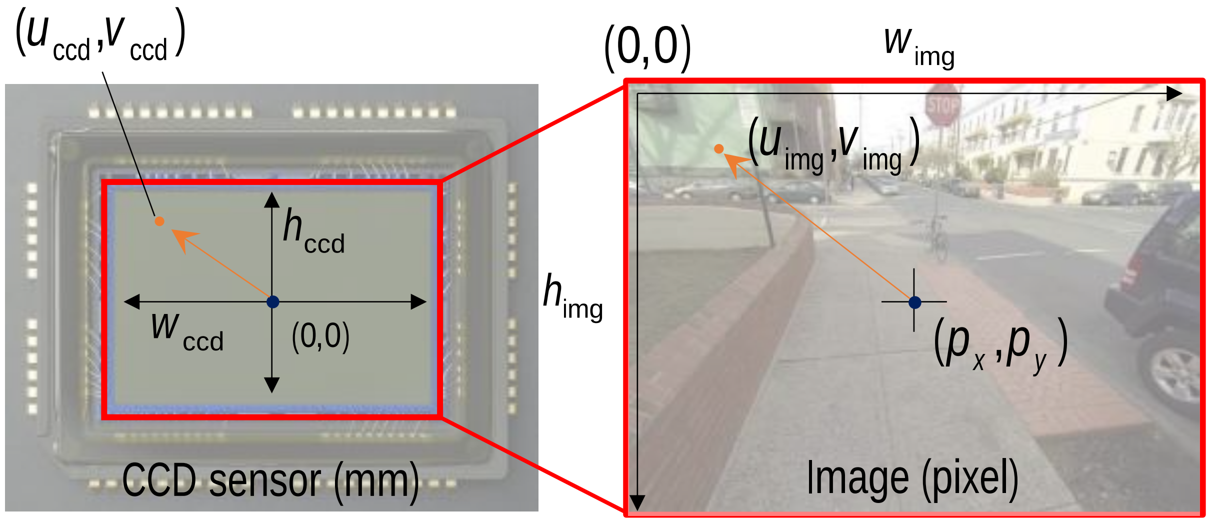


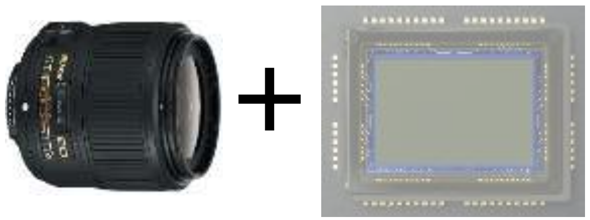
$$u_{img} = f\frac{X}{Z} + p_x \longrightarrow Zu_{img} = fX + p_x Z$$

$$v_{img} = f\frac{Y}{Z} + p_y \longrightarrow Zv_{img} = fY + p_y Z$$

Pixel space   Metric space

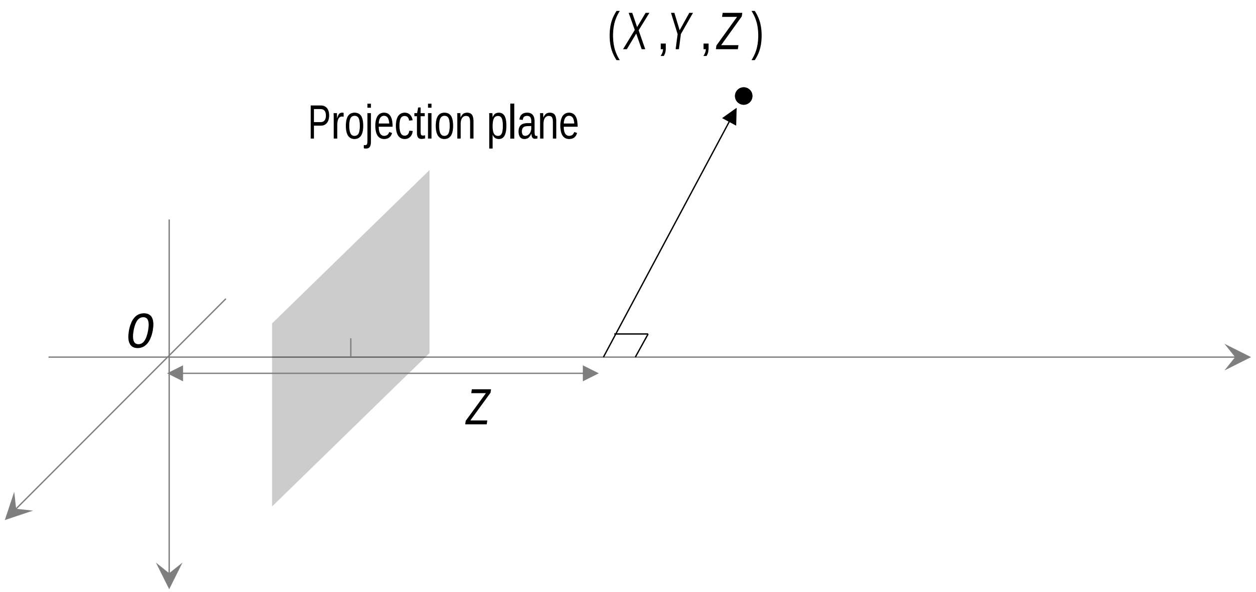
$$\lambda \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \mathrm{K} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad \mathrm{K} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}$$





Camera intrinsic parameter
: metric space to pixel space

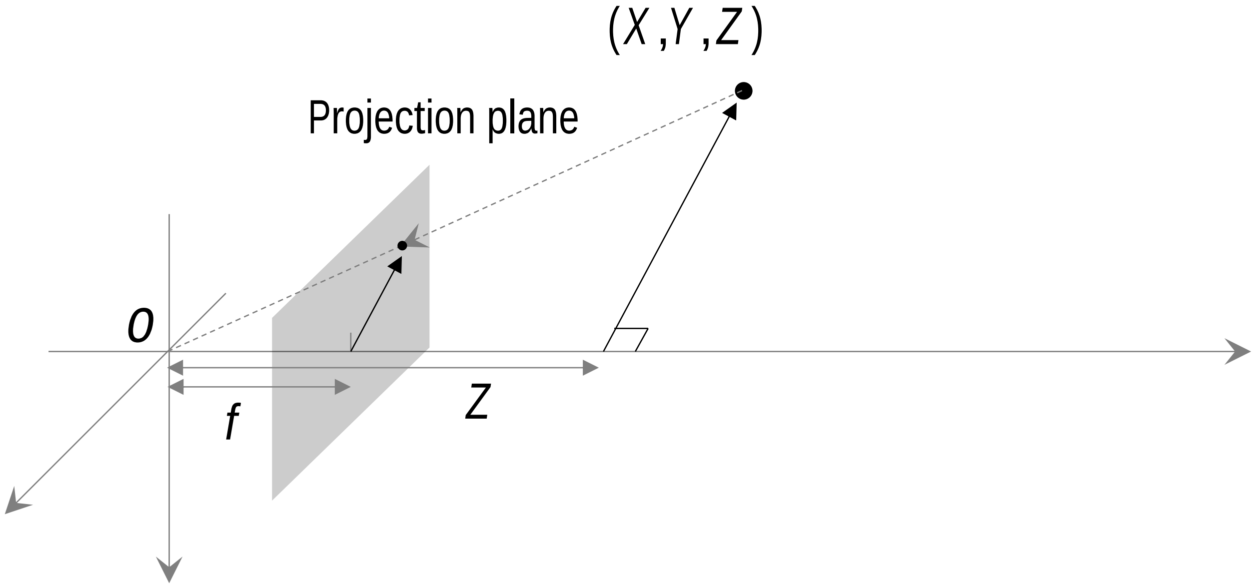
Camera Intrinsic Parameter



Metric space

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Camera Intrinsic Parameter

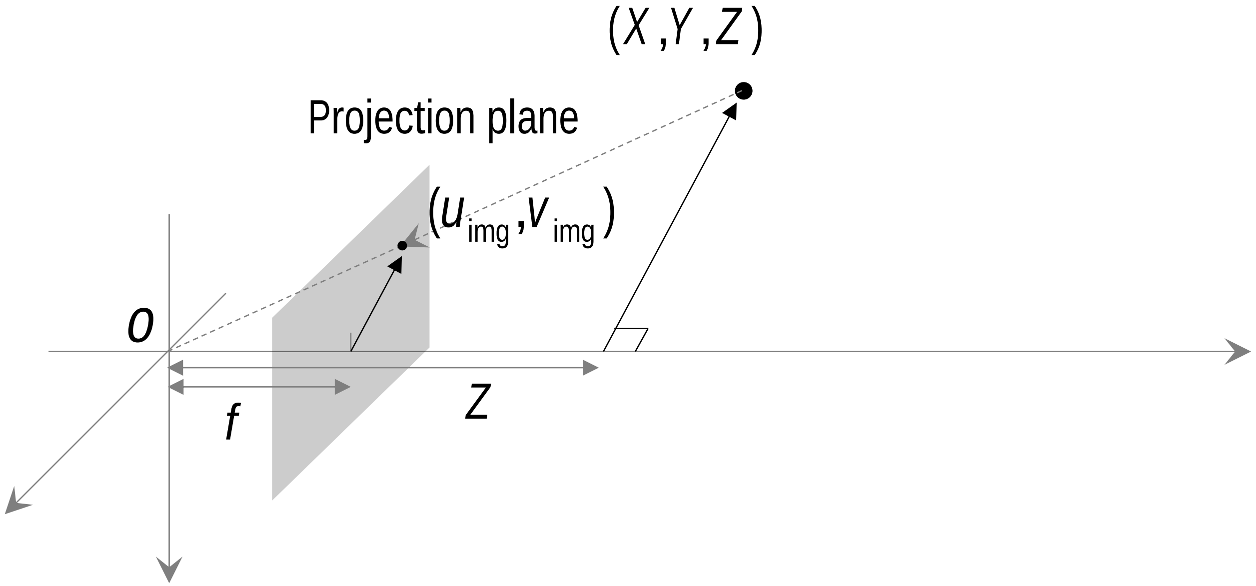


Metric space

K

$$\begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Camera Intrinsic Parameter



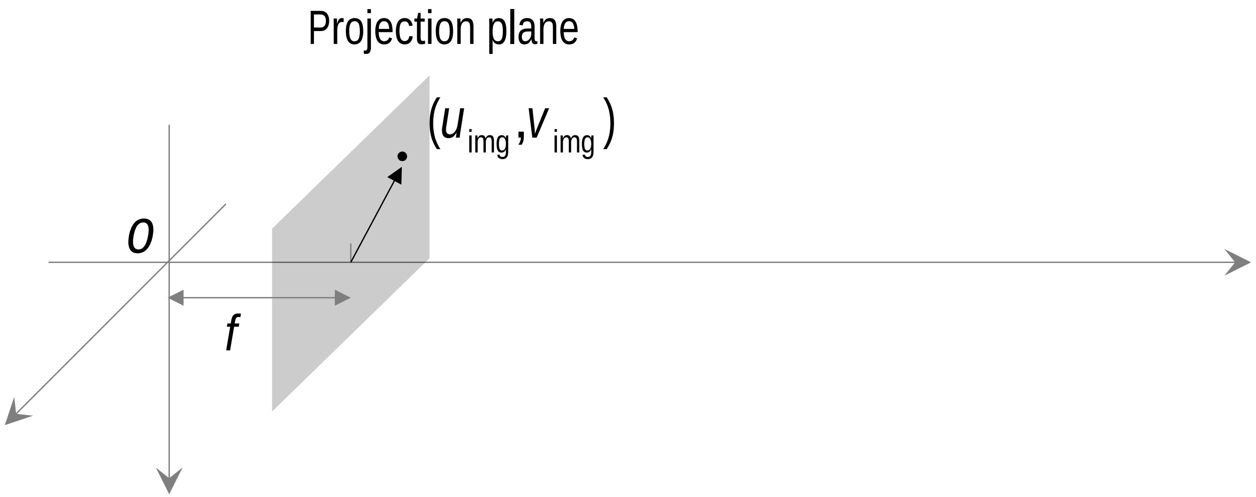
Pixel space

Metric space

$$\lambda \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

K

2D Inverse Projection

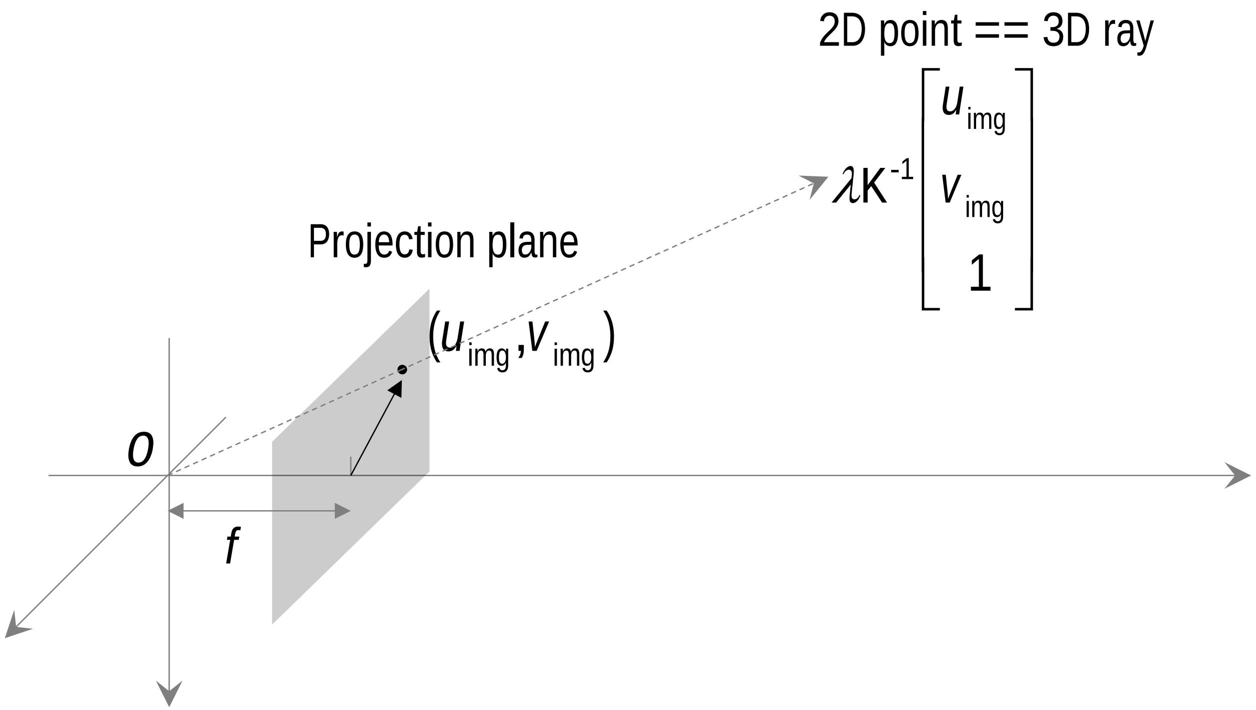


Pixel space | Metric space

$$\lambda \begin{bmatrix} u_{\text{img}} \\ v_{\text{img}} \\ 1 \end{bmatrix} = \mathrm{K} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\begin{bmatrix} u_{\text{img}} \\ v_{\text{img}} \\ 1 \end{bmatrix}$$

2D Inverse Projection

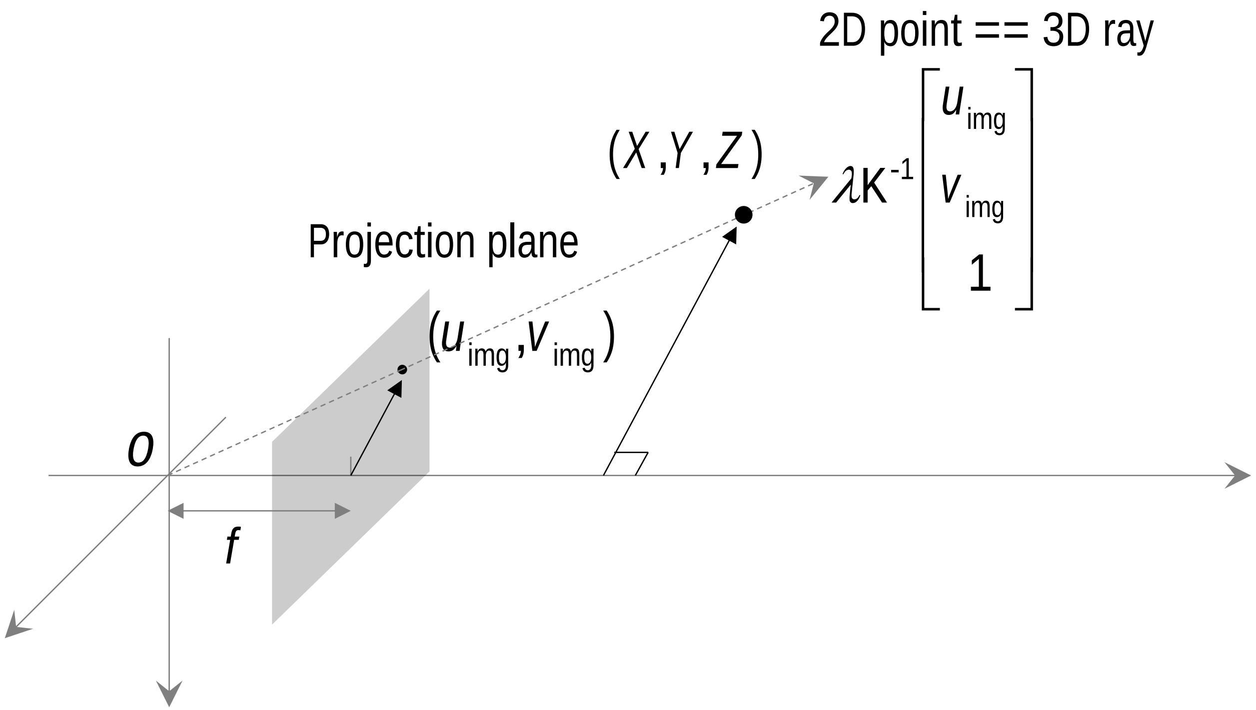


Pixel space — Metric space

$$\lambda \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \mathrm{K} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad \mathrm{K} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}$$

$$\underbrace{\lambda \mathrm{K}^{-1} \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix}}_{\text{3D ray}}$$

2D Inverse Projection

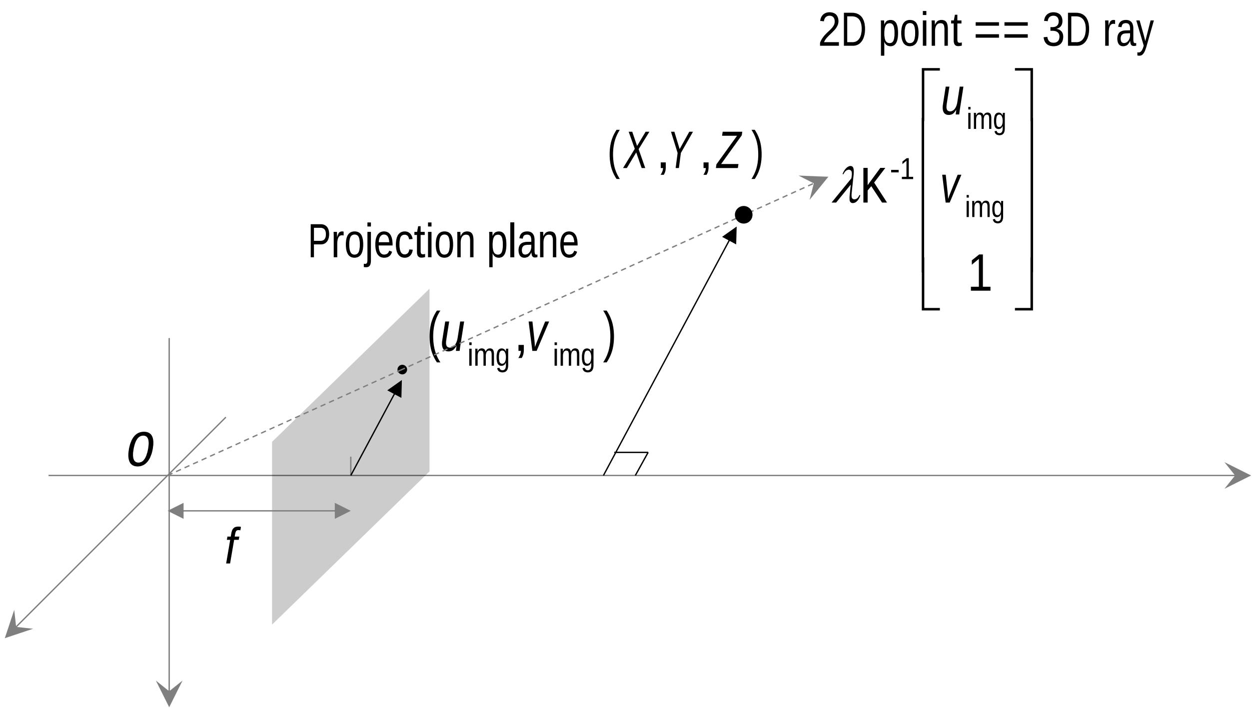


Pixel space — Metric space

$$\lambda \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \mathrm{K} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad \mathrm{K} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}$$

$$\underbrace{\lambda \mathrm{K}^{-1} \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix}}_{\text{3D ray}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

2D Inverse Projection



Pixel space | Metric space

$$\lambda \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix} = \mathrm{K} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad \mathrm{K} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}$$

$$\underbrace{\lambda \mathrm{K}^{-1} \begin{bmatrix} u_{img} \\ v_{img} \\ 1 \end{bmatrix}}_{\text{3D ray}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

The 3D point must lie in
the *3D ray* passing through the origin and 2D image point.