Camera and lens definitions for VFX

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Contents

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Introduction

Filmmaking is a collaborative process, where people from many different specialisms and backgrounds cooperate to make the final product. Ideally, we all have a clear and shared understanding of the various words used to describe cameras and lenses, particularly in VFX work which involves compositing live action and CGI elements. This is important because high accuracy is often needed, and historically there are various inconsistent meanings ascribed to simple sounding terms such as ‘focal length’. This creates a lot of confusion and wasted effort, and is a major barrier to allowing hardware and software from different vendors to interoperate.

This document aims to provide a self-consistent set of definitions, along with just enough technical background to explain why these definitions make sense. The plan is as follows:

- Section 2 discusses the various meanings of the term ‘focal length’, which is probably the single biggest source of confusion when discussing lens characteristics.
- Section 3 defines a physical reference point that can be used to specify physical positions in space (e.g. to define a focus setting).
- Section 4 provides a summary of the definitions.

2.0 There are three different definitions of focal length

The confusion around focal length comes from the fact there are actually three different meanings of the term, each with an important but distinct definition. Understanding 'focal length' comes down to understanding which of these three concepts is being used, and understanding which is needed for the specific application at hand. As a summary:

- **Nominal focal length** is the number printed on the side of a prime lens, e.g. 50 mm. It's used to unambiguously describe which lens is needed for a shot, and gives a good (but approximate) indication of the visual effect the lens will produce. This number is the one used by directors, cinematographers, camera operators, and lens rental houses.

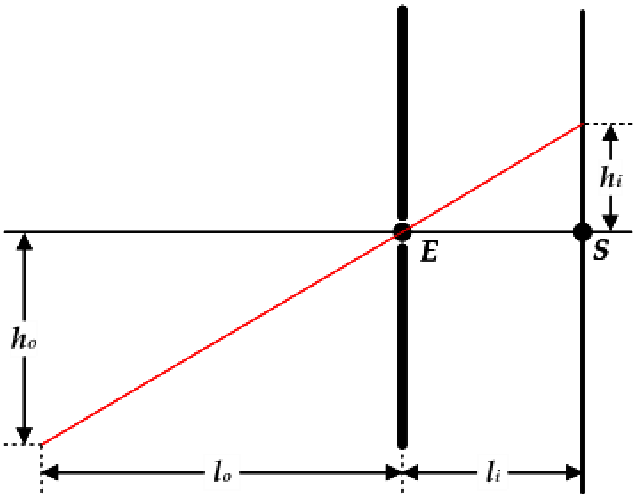
- **Pinhole focal length (PFL)** is used for computer generated imagery (CGI), and more generally throughout the visual effects (VFX) software pipeline. Object modelling software, renderers and matchmoving applications are all based around pinhole camera models, and hence specify lens characteristics in terms of the PFL. When a VFX or matchmove artist talks about focal length, they're probably talking about PFL.

- **Effective focal length (EFL)** is part of a simplified optical model (the 'thick lens model'). This model is important when designing lenses, and understanding certain imaging characteristics (particularly depth of field). When a lens designer talks about focal length, they're probably talking about EFL.

In general, **these three numbers are not the same** and accidentally mixing them up can lead to significant problems when matchmoving, or trying to combine live action and CGI footage.

2.1 Pinhole focal length

Within CGI software, cameras are generally defined mathematically via a pinhole model. This pinhole model allows a point in 3D space to be mapped to a point on a 2D image. The following diagram shows the basic geometry:



where:

- h_i is the image height,
- h_o is the object height,
- l_i is the distance between the pinhole and the image plane (i.e. the pinhole focal length, often just called the focal length in VFX software),
- l_o is distance from the pinhole to the point on the optical axis closest to the object point,
- E is the pinhole location, and
- S is the intersection of the optical axis and the image plane.

The location of the point in the image can be calculated given the relationship:

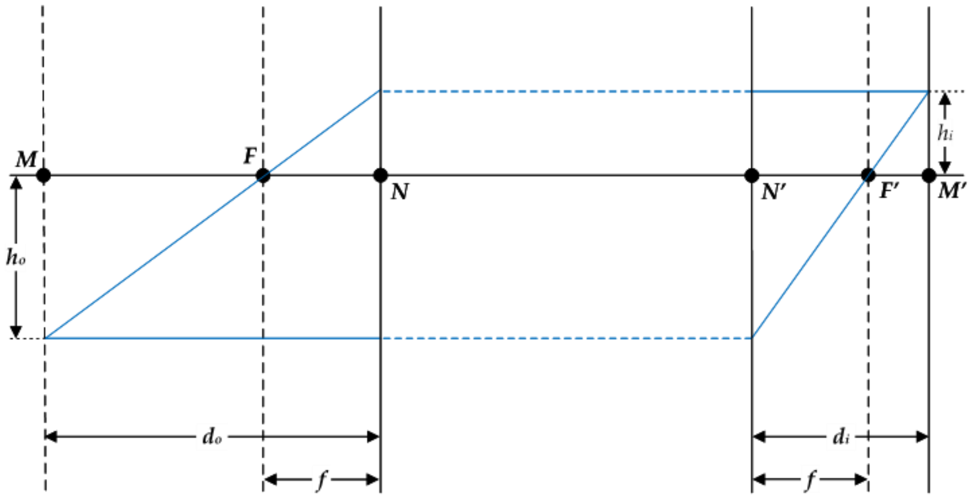
$$\frac{\mathrm{h_i}}{\mathrm{h_o}} = \frac{\mathrm{l_i}}{\mathrm{l_o}}$$

[1]

From a camera/lens modelling perspective, the most important quantity here is the pinhole focal length (PFL), which in the above notation is $\mathrm{l_i}$. Note that often this quantity is given the symbol f, but we avoid that choice here to prevent confusion with the concept of effective focal length discussed in the next section.

2.2 Optical models of lenses

The most basic and important physical model of a lens is the 'thick lens model', which explains how a lens brings rays from an object into sharp focus:



Here:

M is an axial point on the object plane,

M' is an axial point on the image plane,

F and F' are the front and rear focal points respectively,

N and N' are the front and rear nodal points respectively,

f is the effective focal length of the lens,

d_o is the distance from the front nodal point to the point on the optical axis closest to the object point,

d_i is the distance from the rear nodal point to the image plane, and

H_i and H_o are the image and object heights, as in the pinhole model.

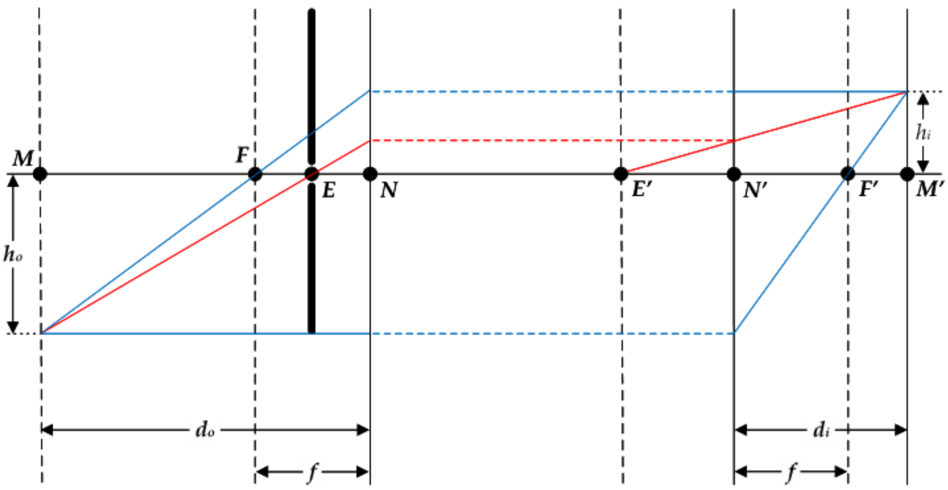
Here, we are assuming that the medium surrounding the lens is the same on both sides, e.g. this is a lens in air. Under this assumption, the focal lengths will be identical on both sides of the lens, and the front and rear principle planes pass through the front and rear nodal points respectively. The principle points (which are important for the definition of effective focal length) are also coincident with the nodal points. Situations which violate this assumption (e.g. an underwater lens) need special care, outside the scope of this document. Note also that the nodal points N and N' are purely modelling terms; they do not correspond to any physical feature on the actual lens or camera.

We can use the following Gaussian lens formula (corresponding to Equation 5d in [1]) to define which objects will be brought into sharp focus:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \qquad [2]$$

The thick lens model is a good approximation to the way that real lenses behave, particularly for rays that are close to the optical axis. Models built around the assumption that rays are close to the optical axis are called paraxial optical models.

The above model is good at specifying which points will be in focus, and the relationship between in-focus points in 3D space and points on the image plane. However, it is not sufficient to understand how out-of-focus points will map onto the image plane. For this, we need to add entrance and exit pupils, which we do by inserting an iris in the optical path:



where:

E is the entrance pupil, and

E' is the exit pupil.

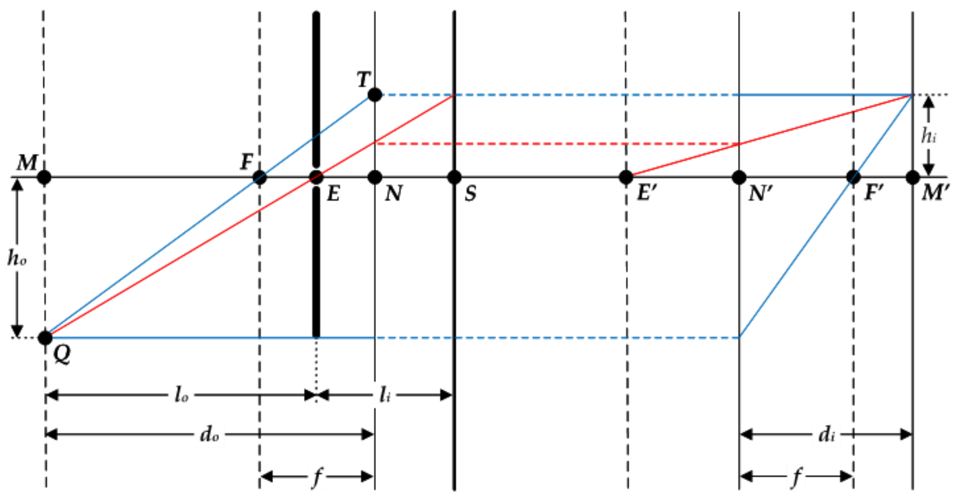
The new ray passes through the centre of the iris. In optical modelling, this is termed a chief ray. As with the nodal points the entrance and exit pupils are purely modelling features; they do not correspond to any physical features in the actual lens. In particular, the entrance pupil does not coincide with the physical location of the iris mechanism in the lens. Indeed, it is not unusual for the entrance pupil to be located outside the lens. The thick line marked E on the above diagram indicates the location of the entrance pupil, not the location of the iris.

In practical terms:

- f is the effective focal length,
- l_o is the distance between the entrance pupil position (E) and the object plane (M), and
- d_o is the distance between the front nodal point (N) and the object plane (M).
- l_i is the pinhole focal length, which is what we need to calculate for CGI work.

When the lens is focussed at infinity, the pinhole focal length and the effective focal length will be the same.

Model on the same diagram:



We now have enough information to define the pinhole focal length l_i in terms of the thick lens model. Start by noting that QMF and TNF are similar triangles. This means that:

$$\frac{h_o}{d_o - f} = \frac{h_i}{f}$$

[3]

which can be rearranged to give

$$\frac{h_o}{h_i} = \frac{d_0}{f} - 1$$

[4]

Then, substituting this into Equation 1 and rearranging gives

$$l_i = \frac{l_o}{d_o/f - 1}$$

[5]

2.3 Talking to optical designers about pinhole focal length

What is needed for CGI work is the pinhole focal length. Unfortunately, this is often not what optical designers provide: they provide the effective focal length and this is not the same thing. Equation 5 shows that these two quantities can be related (i.e. we can work out the pinhole focal length given the effective focal length) but we need some additional information to do that, specifically the relative positions of the front nodal point, the entrance pupil, and the object plane.

In the language of an optical designer, we need:

- Effective focal length (f),
- The entrance pupil position relative to the image plane (EM'),
- The front node position relative to the image plane (NM'),
- The focus setting, which is equivalent to the object plane position relative to the image plane (MM').

Because the entrance pupil, front node, and focus setting are all defined relative to a common reference position (M'), we can calculate l_o by subtracting the entrance pupil position from the focus setting. Similarly we can calculate d_o by subtracting the front node position from the focus setting. We can then use Equation 5 to evaluate the pinhole focal length.

2.4 Practical implications

Some existing lenses provide access to pinhole focal length metadata (e.g. lenses which support the Cooke /i protocol). For other lenses, filmmakers can only obtain pinhole focal length via real-world testing, e.g. camera calibration using a grid, or solving for focal length as part of a match-move.

More lenses could provide pinhole focal length metadata without too much trouble. This document provides everything a lens designer needs to calculate pinhole focal length from their standard optical models.

3.0 The mount is the best physical reference point

When we need to specify a point in space (e.g. a point we wish to focus on), we need a convention for where this point should be measured from. The most common convention is to measure it from the camera's image plane (also referred to as the film plane, or sensor plane). Where other physical points are defined (e.g. the location of the entrance pupil), again we need a convention and again the most common choice is to measure relative to the camera's image plane .

This may suggest that the camera's image plane is the best physical reference point in the overall system, and everything else should be defined relative to that. There are however two major problems with this definition. Firstly, modern digital cameras have several physical structures that comprise the sensor (typically including an antialiasing filter, a microlens array, and the light sensitive semiconductor), none of which are in the exact physical location of the film plane in a traditional camera. Secondly, we need definitions that everyone can agree on, and lens manufacturers can't depend on anything external to their product.

The best solution here is to define these quantities as being relative to the nominal image plane, and defining this as being offset by the nominal mount flange focal distance from the mount flange. So to take a concrete example of setting lens focus with the Arri PL mount:

- The PL mount flange is the fundamental physical reference point,
- The nominal image plane is defined to be exactly 52 mm behind the mount flange, and
- The object we want to focus on is measured relative to the nominal image plane.

The key advantage here is that both camera and lens manufacturers can agree about where the PL mount flange is (as both cameras and lenses have a physical feature at this location), and where the nominal image plane is relative to this.

4.0 Definitions

Nominal focal length	The focal length printed on the side of lens, used to specify which lens is needed for a particular shot. Expected to be close to the effective focal length when the lens is focussed at infinity.
Pinhole focal length	The focal length used within the pinhole camera model used in matchmoving and CGI software.
Effective focal length	Within paraxial optical models, the distance between the principal point and focal point.
Entrance pupil	The *apparent* aperture of the lens, seen from the object side. Provides the best approximation to the location of the pinhole, when compositing live action and CGI footage.
Nominal image plane	The expected location of the image plane of a camera, given the location of the mount flange and the specified flange focal distance. Often used as the origin when specifying points in space (e.g. focus setting, or the entrance pupil position).

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5.0 References

[1] Jenkins, F.A. and White, H.E., Fundamentals of Optics Fourth Edition, McGraw-Hill, 1976.

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