

Draw-Tube Telescope

This three-section telescope is to be designed as a relayed Keplerian.

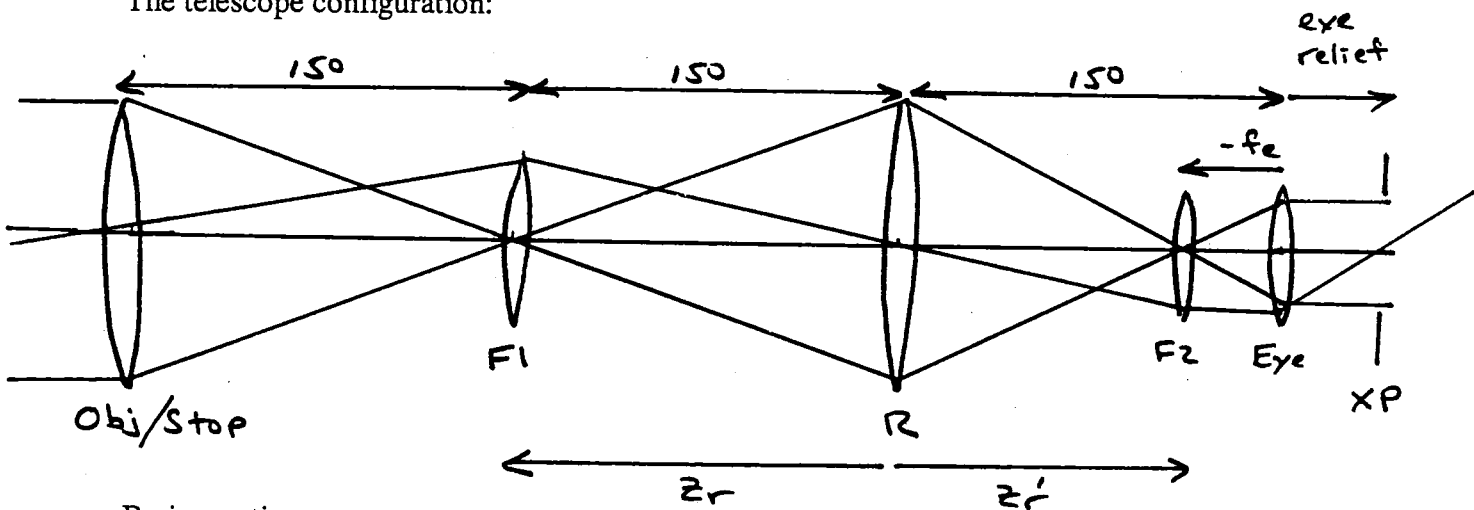
The mechanical constraints require:

- the objective lens must be at the front of tube 1
- the first field lens is at the front of tube 2
- the remaining three lenses must be in tube 3
- the eye lens is at the back of tube 3
- the second field lens is at the front focal point of the eye lens

This arrangement allows the telescope to collapse the length of a single tube.

The maximum entrance pupil diameter occurs by placing the relay lens at the front of tube 3. Since the stop is at the objective, which is imaged onto the relay lens by the first field lens, the size of the relay lens (dictated by the smaller tube three diameter) will limit the stop size and the entrance pupil diameter. The relay lens should be placed as close to the field lens as possible to allow the largest possible stop/objective lens. This 1:1 imaging configuration results in the smallest possible magnification for this pupil imaging.

The telescope configuration:



By inspection:

$$f_{\text{obj}} = 150 \text{ mm}$$

The first field lens works at 1:1

$$f_{F1} = 75 \text{ mm}$$

Because of the 1:1 imaging of the objective lens into the relay lens, the objective lens does not need to be any larger than the relay lens $D_{\text{OBJ}} = D_{\text{RELAY}} = 46 \text{ mm}$. In this case, the objective lens can be considered to be the system stop and in intermediate pupil is located at the relay lens. If a 50 mm diameter objective were used to fill the first tube section, then the relay lens is the stop, and the entrance pupil (diameter = 46 mm) is located at the objective lens.

There are three equations to determine the design:

-the imaging of the intermediate image by the relay lens

$$\frac{1}{z_r'} = \frac{1}{z_r} + \frac{1}{f_R} \quad z_r = -150$$

-the spacing between the relay and eye lenses must equal the tube length

$$z_r' + f_e = 150$$

-the overall system magnifying power

$$MP = - \frac{z_r'}{z_r} \frac{f_{obj}}{f_e} = 15$$

Solving these three simultaneous equations:

$$z_r' = 150 - f_e$$

$$z_r' = -15 z_r f_e / f_{obj}$$

$$150 - f_e = -15 z_r f_e / f_{obj} \quad z_r = -f_{obj}$$

$$150 - f_e = 15 f_e$$

$$16 f_e = 150$$

$$\underline{f_e = 9.375 \text{ mm}}$$

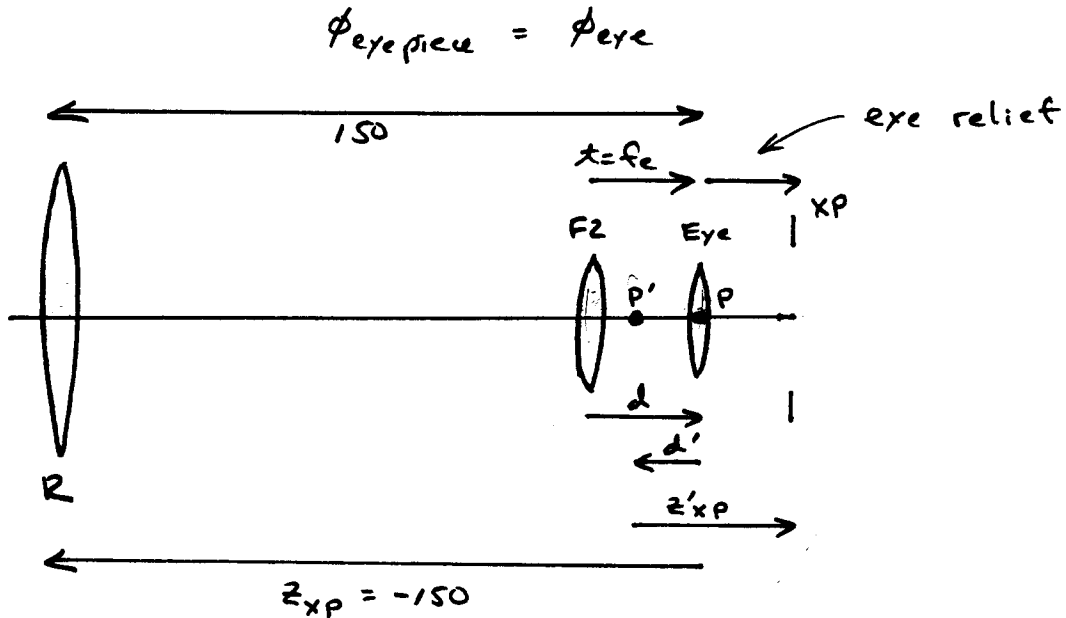
$$\underline{z_r' = 140.625 \text{ mm}}$$

$$\frac{1}{z_r'} = \frac{1}{140.625} = \frac{-1}{150} + \frac{1}{f_R}$$

$$\underline{f_R = 72.581 \text{ mm}}$$

The eye relief determines the focal length of the second field lens. The XP is found by imaging the relay lens (or the image of the stop) into image space:

For an eyepiece with the field lens at the front focal point of the eye lens:



$$\frac{1}{z'_{XP}} = \frac{1}{z_{XP}} + \frac{1}{f_e}$$

$$\frac{1}{z'_{XP}} = \frac{-1}{150} + \frac{1}{9.375}$$

$$z'_{XP} = 10.00 \text{ mm}$$

$$d' = - \frac{\phi_{F2}}{\phi_{\text{eye}}} t = - \frac{f_e}{f_{F2}} f_e$$

$$d' = - f_e^2 / f_{F2}$$

$$d = t = f_e$$

$$\text{Eye Relief} = z'_{XP} + d' = 8.00 \text{ (as specified)}$$

$$d' = -2.00 = -f_e^2 / f_{F2}$$

$$f_{F2} = f_e^2 / 2.00 = (9.375)^2 / 2.00$$

$$\underline{f_{F2} = 43.945 \text{ mm}}$$

Now determine the required lens diameters by tracing a marginal and chief ray.
 Use the HFOV of 1 degree and an initial marginal ray height of 23 mm (half the objective diameter).

$$\bar{u} = \tan 1^\circ = .0175$$

$$a = |y| + |\bar{y}| \text{ for unignitted}$$

	y	u	\bar{y}	\bar{u}	a	D
Objective	23.0	0	0	.0175	23.0	46.0
$x = 150$		-.1533		.0175		
Field 1	0		2.62		2.62	5.24
$x = 150$		-.1533		-.0175		
Relay	-23.0		0		23.0	46.0
$x = 140.625$.1636		-.0175		
Field 2	0		-2.455		2.455	4.91
$x = 9.375$.1636		.0384		
Eye	1.533		-2.10		3.63	7.26
$x = 8.0$		0		.2612		
XP	1.533		0		1.533	3.07

All of these lenses will fit in their respective tube.

Part A Design Summary:

Objective :	$f_{obj} = 150 \text{ mm}$	$D_{obj} = 46 \text{ mm}$	$t = 150 \text{ mm}$
Field 1 :	$f_{F1} = 75 \text{ mm}$	$D_{F1} = 5.24 \text{ mm}$	$t = 150 \text{ mm}$
Relay :	$f_R = 72.581 \text{ mm}$	$D_R = 46 \text{ mm}$	$t = 140.625 \text{ mm}$
Field 2 :	$f_{F2} = 43.945 \text{ mm}$	$D_{F2} = 4.91 \text{ mm}$	$t = 9.375 \text{ mm}$
Eye Lens :	$f_e = 9.375 \text{ mm}$	$D_e = 7.26 \text{ mm}$	$t = 8.00 \text{ mm}$
x P :		$D_{xp} = 3.07 \text{ mm}$	
		$= 46/15 = D_{EP}/M_P$	

Since the EP diameter is 46 mm, the specification for this telescope is 15X46.

Part B Eliminate the second field lens

Eliminating the field lens does not change any of the focal lengths or element spacings. The eye relief changes and the required diameter of the eye lens increases.

For the eyepiece $d'=0$ with no field lens:

$$\text{Eye Relief} = z'_{xp} = \underline{10.00 \text{ mm}}$$

Retrace the chief ray from the Relay to the Eye Lens:

$$\bar{y}_{eye} = \bar{y}_r + \bar{u}_r t \quad t=150$$

$$\bar{y}_{eye} = -2.62 \quad y = 1.53 \text{ (unchanged)}$$

$$a_{eye} = 4.15 \quad \underline{D_{eye} = 8.30 \text{ mm}}$$

The field lens is probably not necessary for this design as we get more eye relief (10.0 instead of 8.0) with a modest increase in eye lens diameter (8.30 instead of 7.26).

Part C Discussion

The mechanical constraint of three equal length tubes (and the resulting fixed lens separations and the 1:1 or near 1:1 imaging) places some significant restrictions on the system design. The two major issues are:

- the forced 1:1 imaging of the objective/stop onto the relay lens by the field lens limits the maximum EP diameter to the relay lens diameter. Ideally we would want the EP diameter to equal the diameter of the first tube section.
- Since the image distance z_{xp}' of the relay lens is smaller than its object distance z_{xp} , the relay lens minifies the second intermediate image. This works against the required telescope MP, and forces the objective-eye lens combination to have extra inherent magnifying power. Usually we would design the relay portion of the telescope to magnify the intermediate images.

In order to get around these problems, we would actually like:

- the separation between the objective and the first field lens to be larger than the first field lens to relay separation (reduces the magnitude of the magnification of the pupil and allows a larger EP). This change also will reduce the required speed of the relay lens. (This argues for placing all of the elements except the objective in the third tube section.)
- the first field lens to relay lens separation should be shorter than the relay lens to second field lens separation (the relay lens magnifies the intermediate image).

This would require a long tube-short tube-long tube telescope configuration.

In a three tube configuration, the first tube can be made longer, but the third tube must be the same length or shorter than the middle tube. This allows the telescope to collapse without crashing into one of the lenses. The proper EP can be obtained, but the relay still works at the wrong magnification.

Using a larger number of tube sections overcomes this limitation by providing more mounting location options for the lenses. For example, if the telescope is seven or eight sections long, the desired long-short-long arrangement can be obtained:

- three sections for the objective to first field lens separation
- one or two sections for the first field lens to relay separation
- three or four elements for the relay to eyepiece separation

Of course, other combinations are possible.

In practice, the maximum power of the eye lens limits the available system FOV. If the system FOV is increased much beyond +/- 1 degree, the required eye lens becomes $f/1$ or faster.