### 3.2.3 The system's detector

The influence coefficients for the system's detector are the same as those for the single lens system:

$$Tx_i/Tx_d = -1$$
$$Ty_i/Ty_d = -1$$
$$Tz_i/Tz_d = -1$$
$$Rx_i/Rx_d = -1$$
$$Ry_i/Ry_d = -1$$
$$Rz_i/Rz_d = -1.$$

### 3.2.4 Effective focal length of multilens systems

Calculating the effective focal length of a system provides a useful quality metric; it tells the engineer how faithfully the physical optical prescription data has been interpreted.

The effective focal length of a system of lenses can be determined from the Gaussian prescription data of the lenses. The process starts by combining the first two lenses into a doublet and calculating the Gaussian properties of the doublet (Fig. 3.9). If the first lens (lens a) has the Gaussian properties $f_a$, $H_{1a}$, $H_{2a}$, and $p_a$, and the second lens (lens b) has the Gaussian properties $f_b$, $H_{1b}$, $H_{2b}$, and $p_b$, then the Gaussian focal length, $f_{ab}$, of the doublet can be calculated as

$$f_{ab} = f_a f_b/(f_a + f_b - pair_a),$$

where the variable *pair* is the principal air thickness between lenses. The position *Ba* of the doublet's first focus $(f_1)_{ab}$ relative to the first principal point of lens a $(P_1)_a$ can be calculated by

$$Ba = f_{ab}(f_b - pair_a)/f_b,$$

and the position *Bb* of the doublet's second focus $(f_2)_{ab}$ can be calculated by

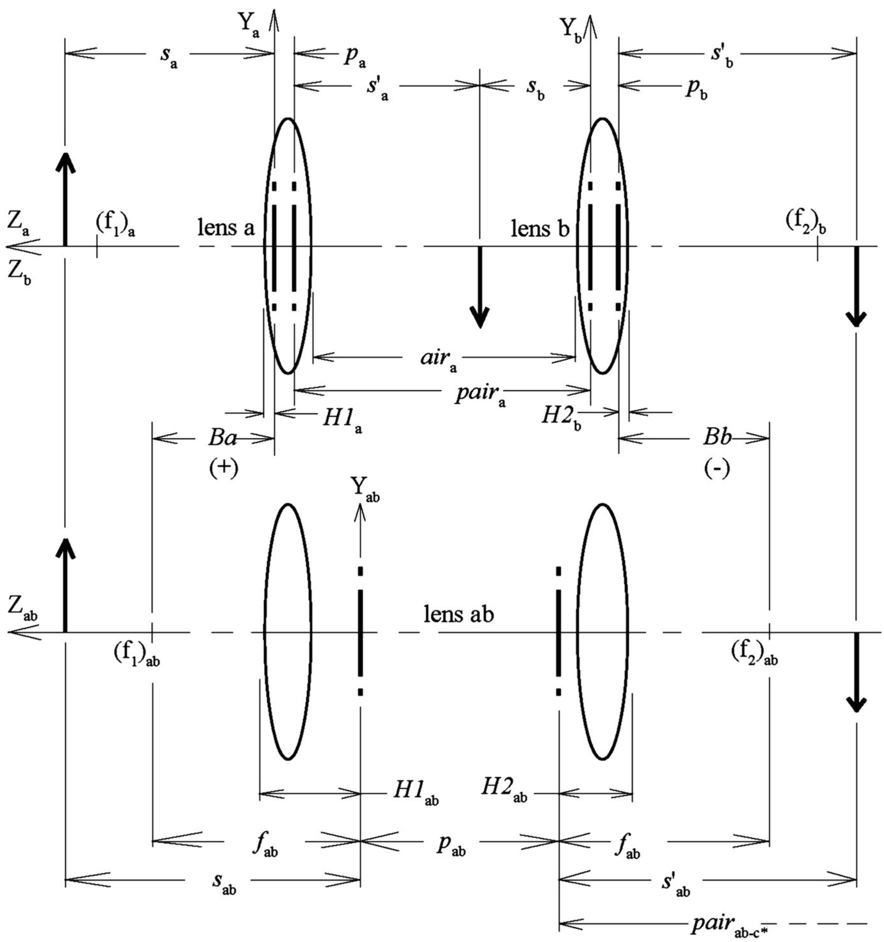
$$Bb = -f_{ab}(f_a - pair_a)/f_a.$$

The principal thickness of the doublet $p_{ab}$ can be calculated by

$$p_{ab} = Ba + p_a + pair_a + p_b - Bb - 2f_{ab}$$

and

$$pair_{ab} = pair_b + Bb + f_{ab}.$$




$$f_{ab} = f_a f_b/(f_a + f_b - pair_a) \qquad p_{ab} = Ba + p_a + pair_a + p_b - Bb - 2f_{ab}$$
$$Ba = f_{ab}(f_b - pair_a)/f_b \qquad H1_{ab} = H1_a + Ba - f_{ab}$$
$$Bb = -f_{ab}(f_a - pair_a)/f_a \qquad H2_{ab} = H2_b + Bb + f_{ab}$$
$$M_{ab} = M_a M_b = s'_{ab}/s_{ab} \qquad pair_{ab} = pair_b + Bb + f_{ab}$$

**Figure 3.9** Gaussian properties of a lens doublet.[1] (Figure adapted from Ref. 3.)

The position of the doublet's principal points, $H_{1ab}$ and $H_{2ab}$, with respect to the first and last vertices of the lenses can be determined from the geometry. The magnification of the doublet is

$$M_{ab} = M_a M_b.$$

The doublet can be increased to a triplet by adding another lens and recalculating the properties with the initial doublet as lens a, and the new lens

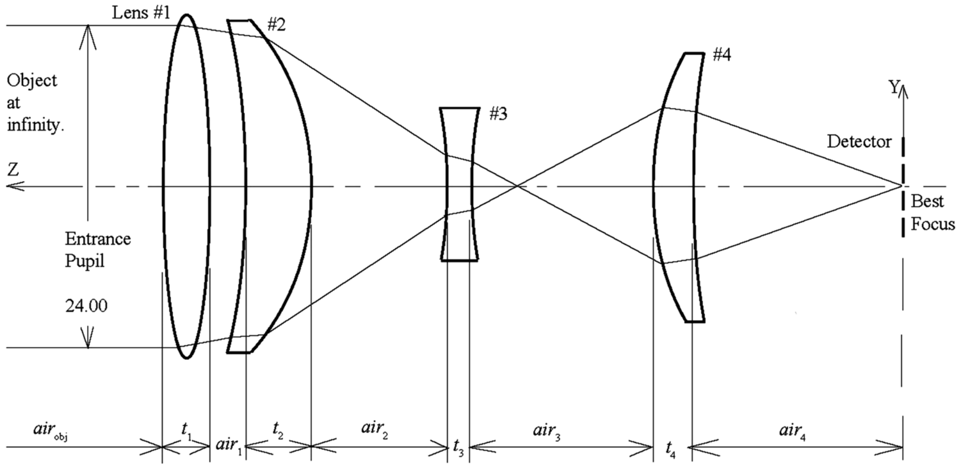



**Figure 3.10** A four-lens infrared receiver.[1]

**Table 3.4** Optomechanical prescription data for the infrared receiver.

| Surface | Element | Radius | Index | Thickness |
|---|---|---|---|---|
| 1 | Obj. | Inf. | 1.000 | Inf. |
| 2 | 1 | −300 | 4.0026 | 2.000 |
| 3 | 1 | 300 | 1.0000 | 5.3566 |
| 4 | 2 | 110 | 4.0026 | 3.4500 |
| 5 | 2 | 55 | 1.0000 | 17.7750 |
| 6 | 3 | 310 | 4.0026 | 2.0000 |
| 7 | 3 | −215 | 1.0000 | 11.9417 |
| 8 | 4 | −11 | 4.0026 | 1.5000 |
| 9 | 4 | −22 | 1.0000 | 20.4727 |
| 10 | Det. | Inf. | 1.0000 | — |

as lens b. The process is repeated, adding one lens at a time, until all of the lenses in the system have been included.

### 3.2.5 Example: An infrared receiver

A four-lens infrared receiver (Fig. 3.10) has been optically designed with the physical optical prescription provided in Table 3.4. The effective focal length of this system is reported to be −51.579012. The dimensional units of this prescription are inches and have been converted to the mechanical sign conventions. The engineer wants to develop the optomechanical constraint equations.

#### 3.2.5.1 The Gaussian prescription

The first task is to derive the Gaussian prescription (Table 3.5) from the optomechanical prescription (Table 3.4) using the equations of Section 1.6:

**Table 3.5** The Gaussian prescription data for the infrared receiver.

| Element | $f$ | $H_1$ | $H_2$ | $p$ | pair |
|---|---|---|---|---|---|
| Obj. | Inf. | 0.0 | 0.0 | 0.0 | Inf. |
| 1 | 50.081936 | −0.2504639 | 0.2504639 | 1.4990722 | 7.2534706 |
| 2 | 34.98851 | −1.6464068 | −0.82320338 | 2.6267966 | 17.246002 |
| 3 | −42.160333 | −0.29420554 | 0.20404578 | 1.5017487 | 11.805767 |
| 4 | 6.6470266 | 0.33997836 | 0.67995673 | 1.1600216 | 21.152657 |
| Det. | Inf. | 0.0 | 0.0 | 0.0 | 0.0 |

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_2} - \frac{1}{R_1} + \frac{t(n-1)}{nR_1R_2}\right],$$

$$H_1 = \frac{-ft(n-1)}{nR_2},$$

$$H_2 = \frac{-ft(n-1)}{nR_1},$$

$$p = t\left[1 - f(n-1)\left(\frac{1/R_2 - 1/R_1}{n}\right)\right].$$

The variable *pair* (the principal air thickness between lenses) is the distance between $P_2$ of one element and $P_1$ of the next element in Fig. 3.11. It is analogous to the air thickness, *air*, between the lens vertices ($V_2$ of one element and $V_1$ of the next element) in the physical optical prescription (see Fig. 3.10).

The data in Table 3.5 are then used to calculate the effective focal length of the four-lens system. For the infrared receiver quadruplet in Fig. 3.10, the focal length of the first element is

$$f_1 = 50.08.$$

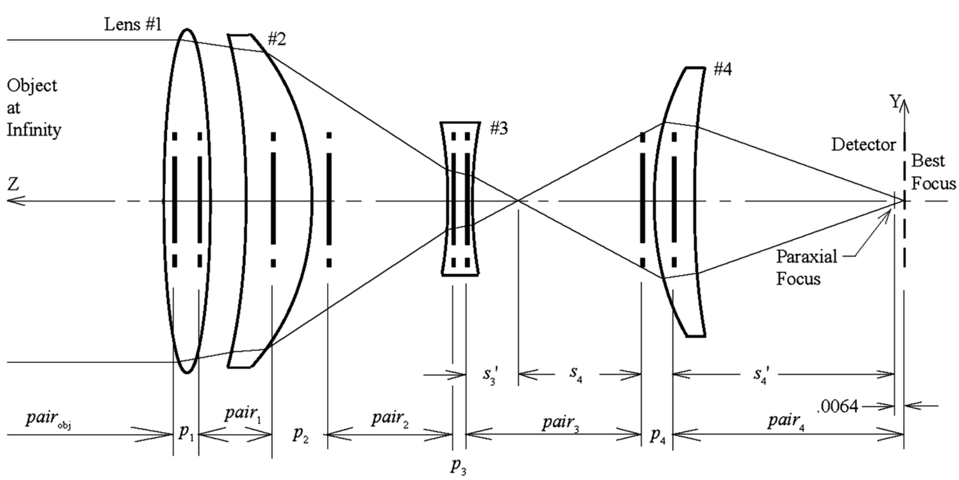



**Figure 3.11** The principal air thicknesses *pair* for the receiver.[1]

Combining $f_1$ with the second lens, the effective focal length of the doublet is

$$f_{1\text{-}2} = 22.52.$$

Combining the 1-2 doublet with the third lens, the effective focal length of the resulting triplet is

$$f_{1\text{-}3} = 23.65.$$

Combining the 1-3 triplet with the fourth (and final) lens of the system, the system's effective focal length is

$$f_{1\text{-}4} = -51.58.$$

This effective focal length compares favorably with the effective focal length (*efl*) from the optical design code,

$$efl = -51.579012,$$

and provides confidence that the physical optical prescription has been properly interpreted.

#### 3.2.5.2 Objects, images, and magnifications

Next, the engineer locates all of the intermediate objects and images, and calculates the element magnifications (Table 3.6) from the equations, noting that an element's object distance, $s$, is calculated from the properties $s'$ and *pair* of the preceding element, as shown for elements 3 and 4 in Fig. 3.11:

$$s = s'_{\text{elem-1}} + pair_{\text{elem-1}},$$
$$s' = 1/(1/s - 1/f),$$
$$M = s'/s.$$

The properties of element 4 are calculated here, as an example:

$$s_4 = s'_3 + pair_3 = -2.111479 + 11.805767 = 9.694288,$$
$$s'_4 = 1/(1/s_4 - 1/f_4) = 1/(1/9.694288 - 1/6.647027) = -21.14626,$$
$$M_4 = s'_4/s_4 = -21.14626/9.694288 = -2.181311.$$

Note that the Gaussian image does not register exactly on the detector; it is 0.0064 inches in front of the detector. This is because the optical

**Table 3.6** Objects, images, and magnifications for the infrared receiver.

| Element | $f$ | $s$ | $s'$ | $M$ |
|---|---|---|---|---|
| Obj. | Inf. | 0.0 | 0.0 | 1.0 |
| 1 | 50.081936 | Inf. | −50.08194 | 0.0 |
| 2 | 34.98851 | −42.82846 | −19.25678 | 0.4496257 |
| 3 | −42.160333 | −2.010775 | −2.111479 | 1.050082 |
| 4 | 6.6470266 | 9.694288 | −21.14626 | −2.181311 |
| Det. | Inf. | 6.39518E-3 | 6.39518E-3 | 1.0 |