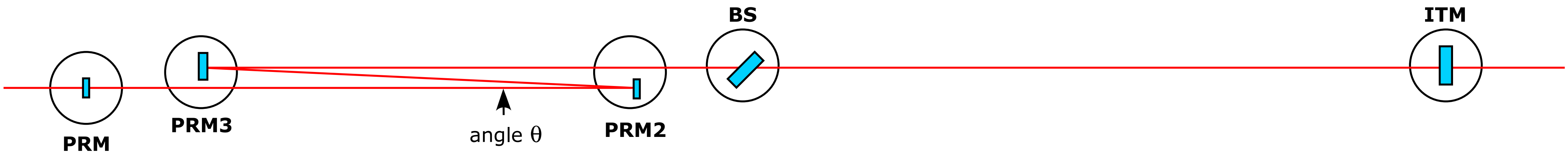
Telescope Optimization



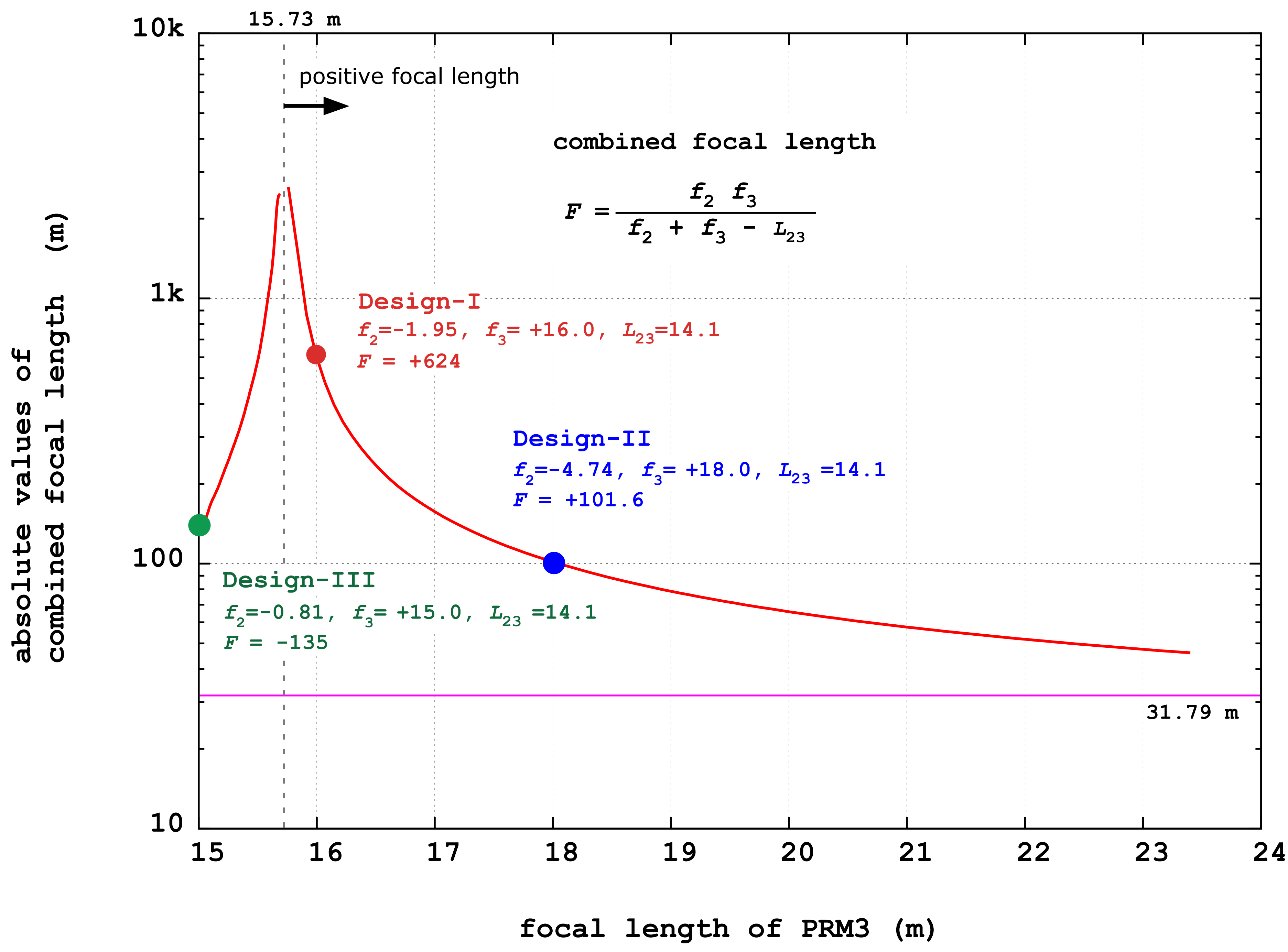
上図の様な folded telescope により Power Recycling Cavity (PRC)

および Signal Recycling Cavity (SRC) における Gouy phase を約 20 度

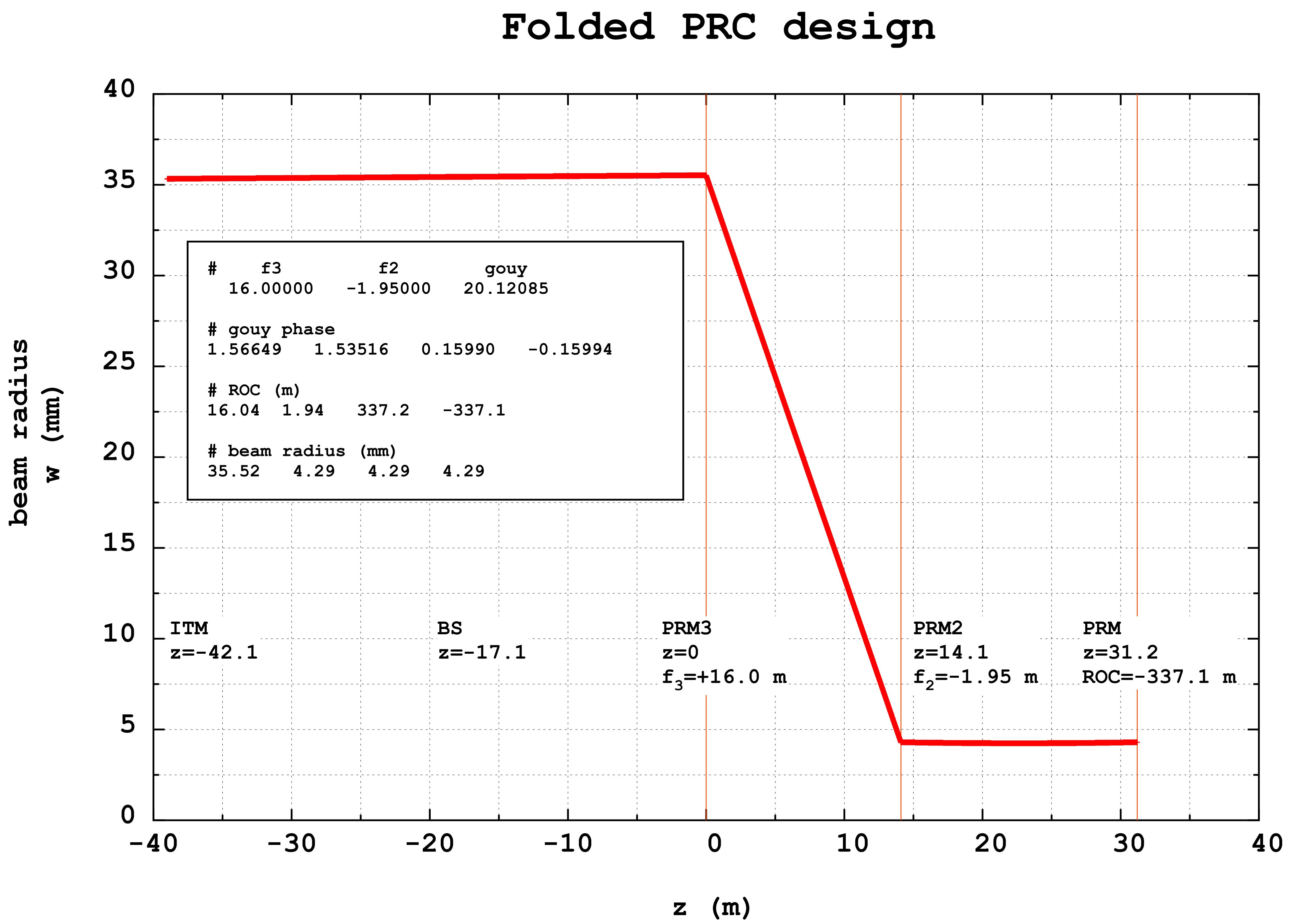
に設定するデザインを検討中である。

ここでは、そのような telescope の設計許容値について評価し、feasibility の

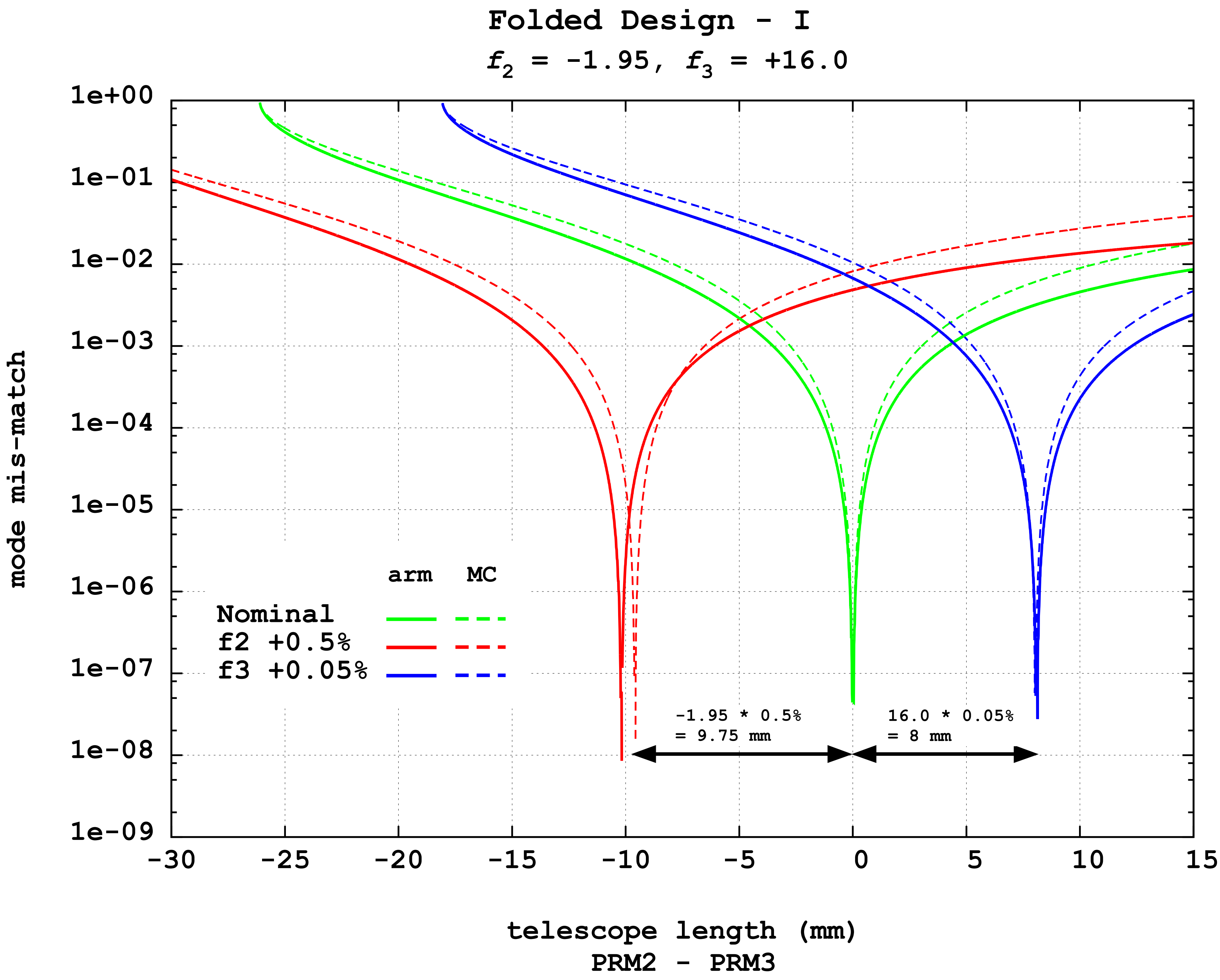
観点から最適な telescope 設計について考える。



15.73 m
10k
1k
100
10
positive focal length
combined focal length
$F = \dfrac{f_2\ f_3}{f_2 + f_3 - L_{23}}$
Design-I
f_2=-1.95, f_3= +16.0, L_{23}=14.1
F = +624
Design-II
f_2=-4.74, f_3= +18.0, L_{23} =14.1
F = +101.6
Design-III
f_2=-0.81, f_3= +15.0, L_{23} =14.1
F = -135
31.79 m
15
16
17
18
19
20
21
22
23
24
absolute values of combined focal length (m)
focal length of PRM3 (m)



Folded PRC design
beam radius
w (mm)
z (m)
40
35
30
25
20
15
10
5
0
-40
-30
-20
-10
0
10
20
30
40
f3 f2 gouy
16.00000 -1.95000 20.12085
gouy phase
1.56649 1.53516 0.15990 -0.15994
ROC (m)
16.04 1.94 337.2 -337.1
beam radius (mm)
35.52 4.29 4.29 4.29
ITM
z=-42.1
BS
z=-17.1
PRM3
z=0
f3=+16.0 m
PRM2
z=14.1
f2=-1.95 m
PRM
z=31.2
ROC=-337.1 m



Folded Design - I
f_2 = -1.95, f_3 = +16.0
mode mis-match
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
-30
-25
-20
-15
-10
-5
0
5
10
15
telescope length (mm)
PRM2 - PRM3
arm
MC
Nominal
f2 +0.5%
f3 +0.05%
-1.95 * 0.5%
= 9.75 mm
16.0 * 0.05%
= 8 mm

Folded Design - II f_2=-4.74, f_3= +18.0, L_{23} =14.1

combined focal length

$$F = \frac{f_2 \; f_3}{f_2 + f_3 - L_{23}}$$

nominal

f_2=-4.74, f_3= +18.0, L_{23}=14.1	$f_2 + f_3 - L_{23}$ = -0.84 F = 101.6

L_{23} +5mm

f_2=-4.74, f_3= +18.0, L_{23}=14.105	$f_2 + f_3 - L_{23}$ = -0.845 F = 101.0

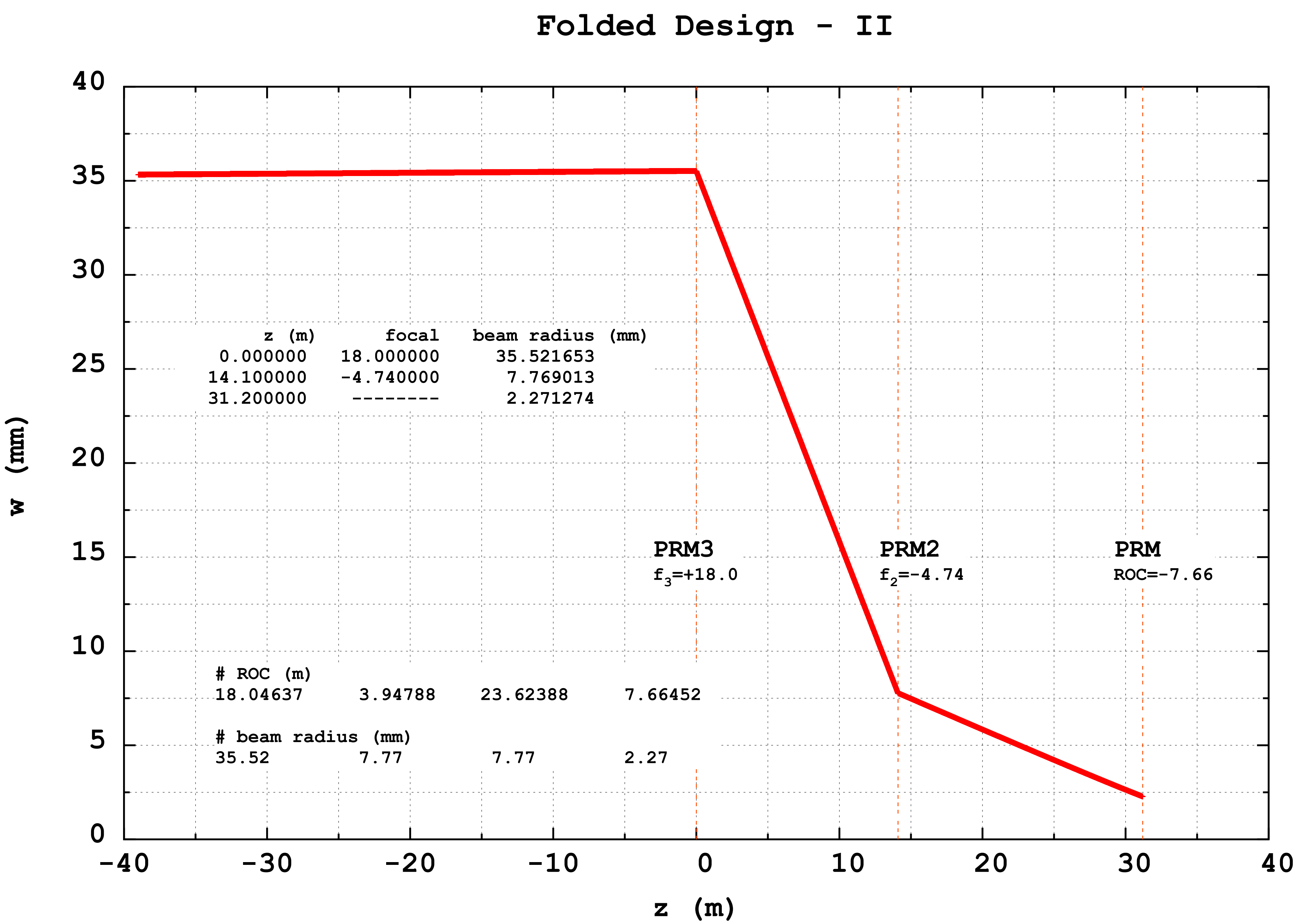
f_2 error

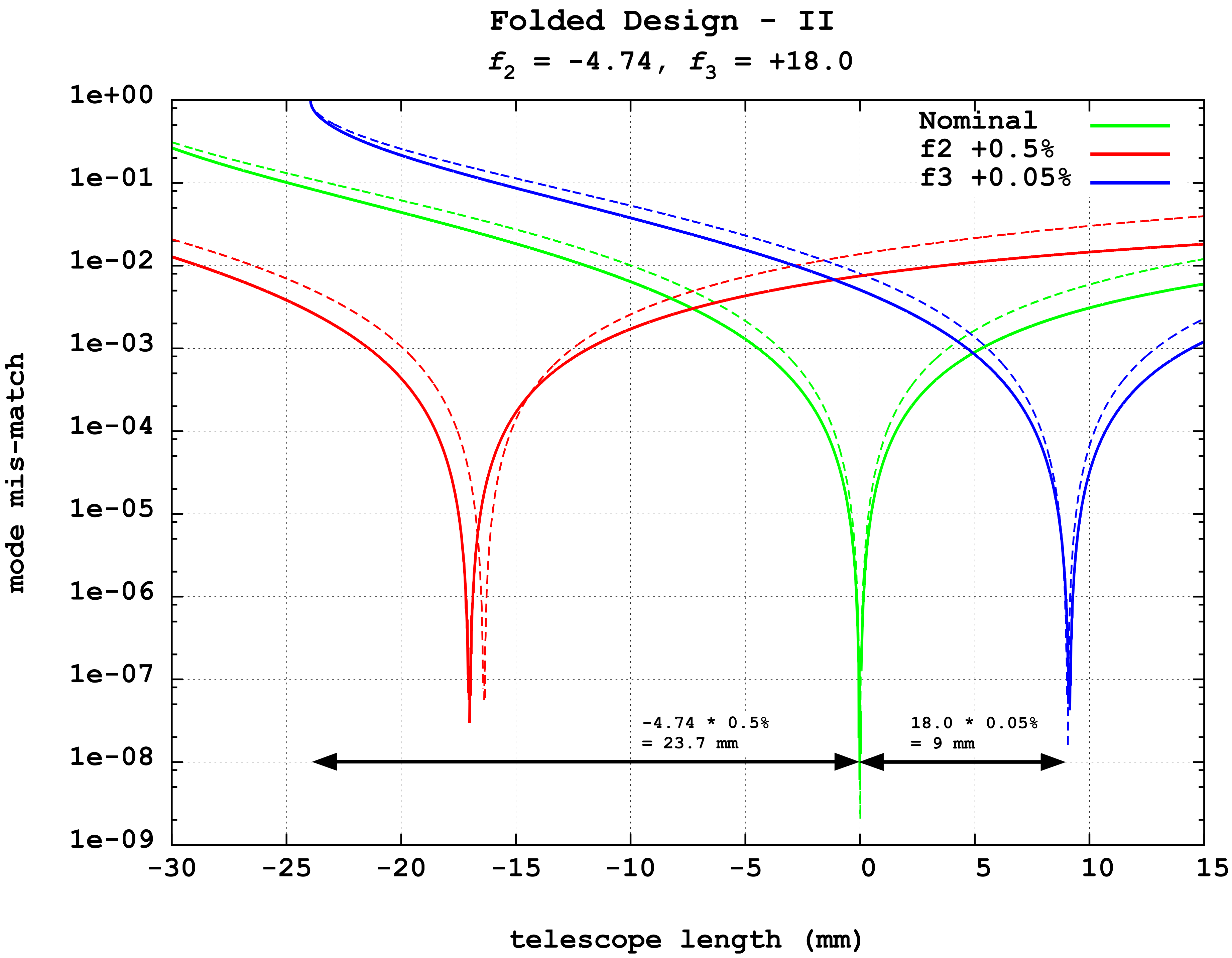
0.5% * 5/17 = 1.5e-3

f_3 error

5e-3/18.0 = 2.8e-4

This design has no merit.


Folded Design - II
z (m) focal beam radius (mm)
0.000000 18.000000 35.521653
14.100000 -4.740000 7.769013
31.200000 -------- 2.271274
PRM3
f_3=+18.0
PRM2
f_2=-4.74
PRM
ROC=-7.66
# ROC (m)
18.04637 3.94788 23.62388 7.66452
beam radius (mm)
35.52 7.77 7.77 2.27
w (mm)
z (m)
0
5
10
15
20
25
30
35
40
-40
-30
-20
-10
0
10
20
30
40



Folded Design - II
f_2 = -4.74, f_3 = +18.0
Nominal
f2 +0.5%
f3 +0.05%
-4.74 * 0.5%
= 23.7 mm
18.0 * 0.05%
= 9 mm
mode mis-match
telescope length (mm)
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
-30
-25
-20
-15
-10
-5
0
5
10
15

Folded Design - III f_2=-0.81, f_3= +15.0, L_{23} =14.1

combined focal length

$$F = \frac{f_2 \; f_3}{f_2 + f_3 - L_{23}}$$

nominal

f_2=-0.81, f_3= +15.0, L_{23}=14.1	$f_2 + f_3 - L_{23}$ = +0.09 F = -135.0

L_{23} +5mm

f_2=-0.81, f_3= +15.0, L_{23}=14.105	$f_2 + f_3 - L_{23}$ = +0.085 F = -142.9

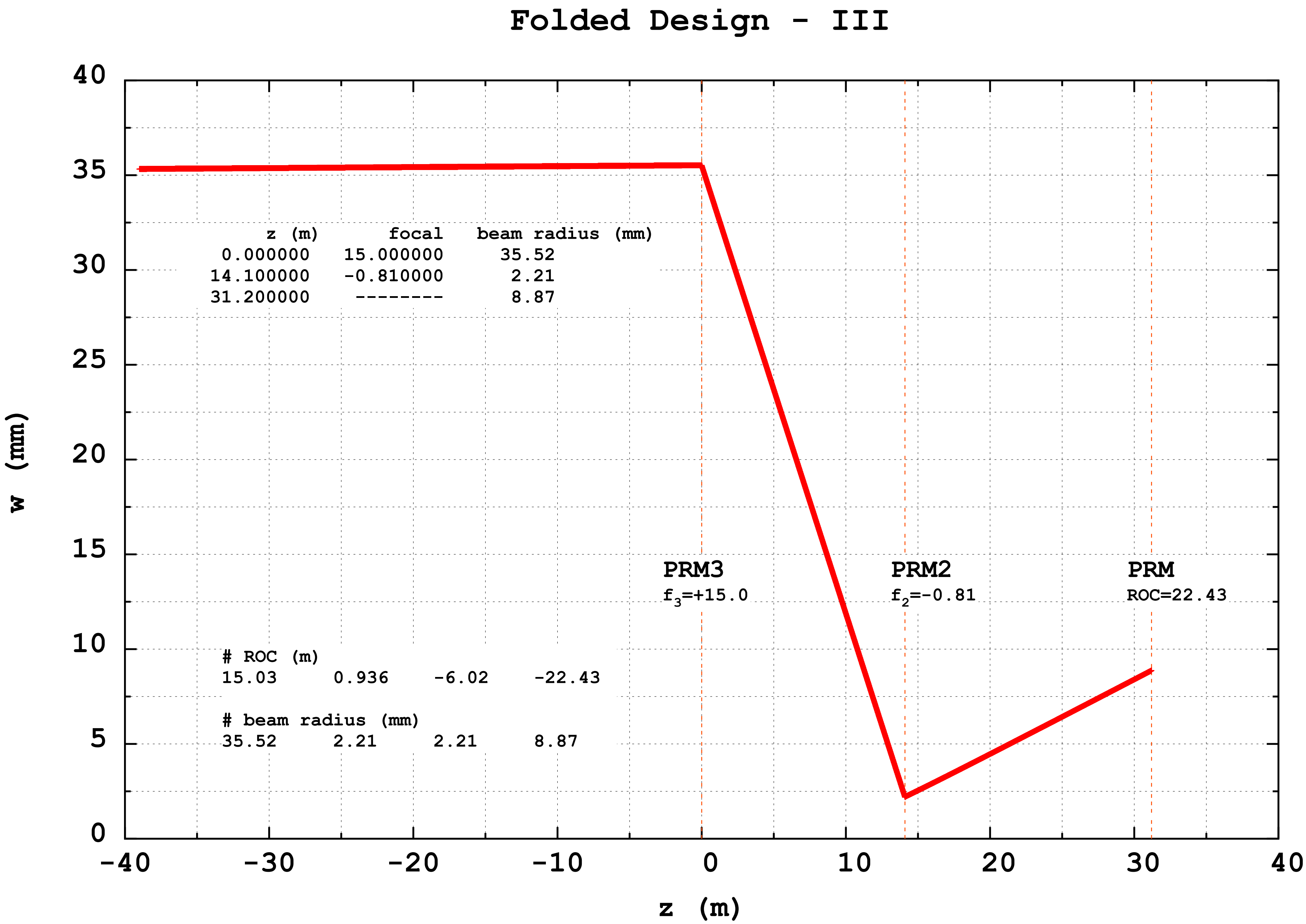
f_2 error

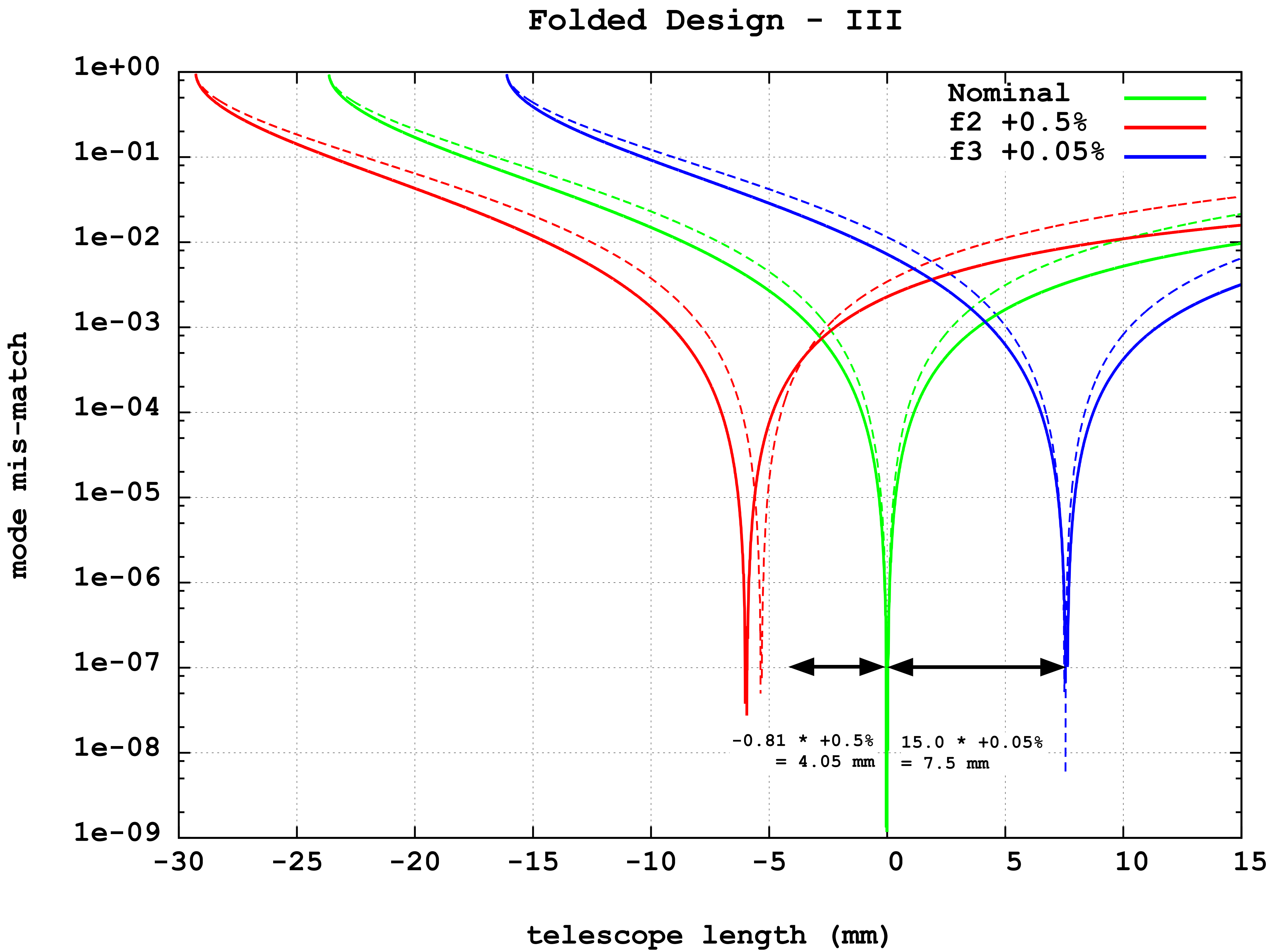
0.5% * 5/17 = 1.5e-3

f_3 error

5e-3/15.0 = 3.3e-4

This design has no significant merit.


Folded Design - III
z (m) focal beam radius (mm)
0.000000 15.000000 35.52
14.100000 -0.810000 2.21
31.200000 --------- 8.87
ROC (m)
15.03 0.936 -6.02 -22.43
beam radius (mm)
35.52 2.21 2.21 8.87
PRM3
f3=+15.0
PRM2
f2=-0.81
PRM
ROC=22.43
w (mm)
z (m)
0
5
10
15
20
25
30
35
40
-40
-30
-20
-10
0
10
20
30
40

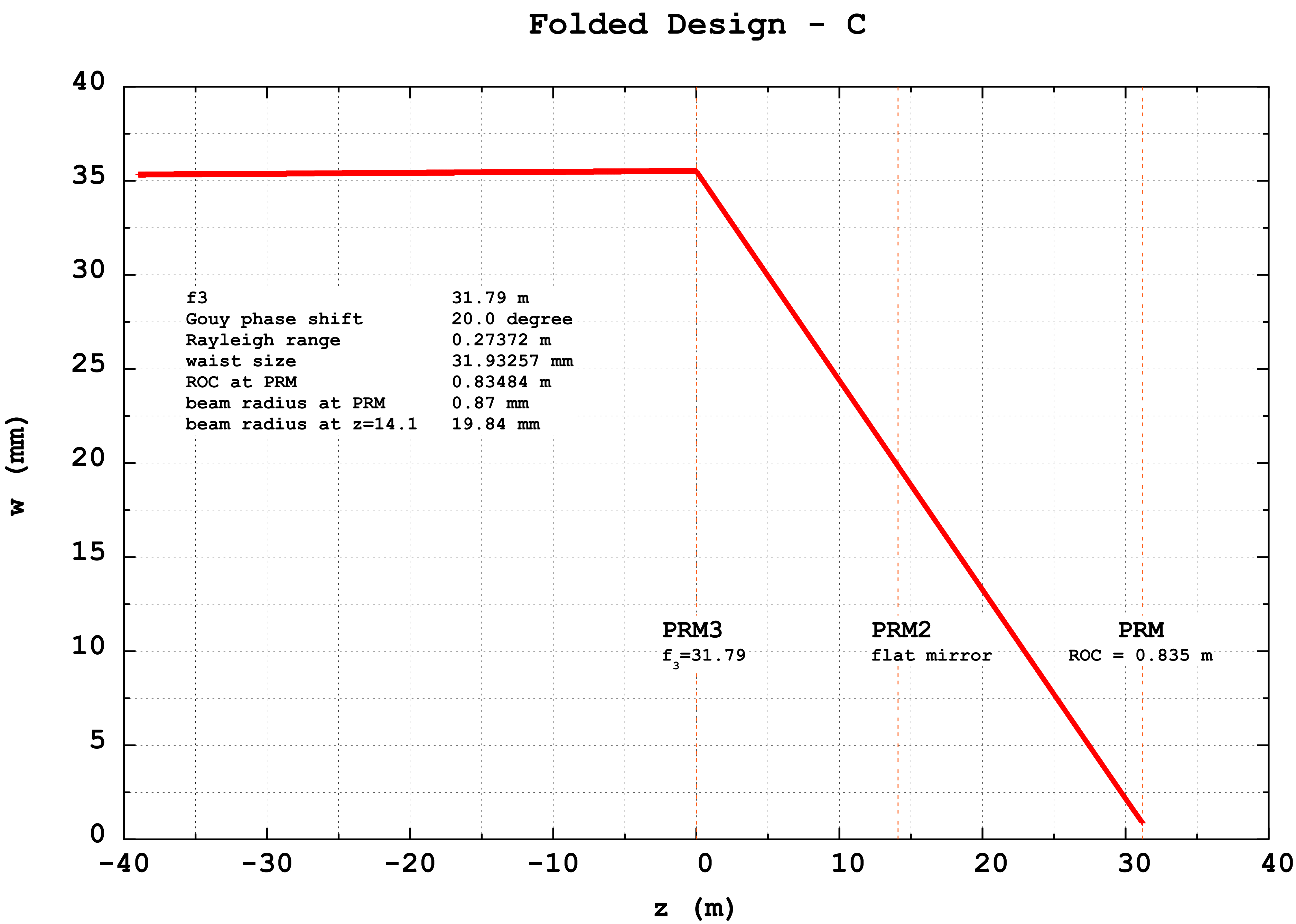


Folded Design - III
mode mis-match
telescope length (mm)
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
-30
-25
-20
-15
-10
-5
0
5
10
15
Nominal
f2 +0.5%
f3 +0.05%
-0.81 * +0.5%
= 4.05 mm
15.0 * +0.05%
= 7.5 mm

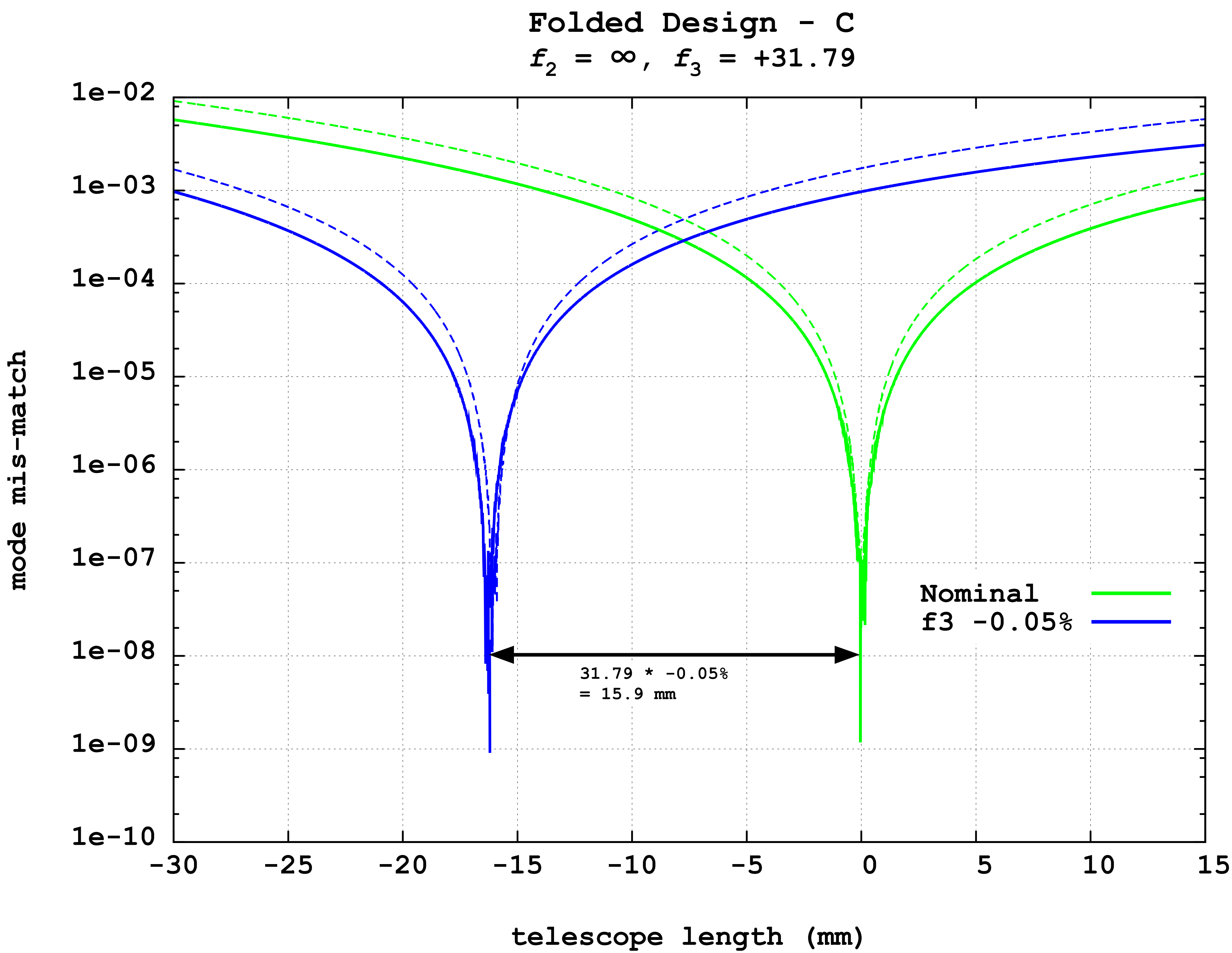
Folded Design - C $f_2=\infty$ (flat), $f_3= +31.79$, $L_{23} =14.1$

combined focal length

$$F = \frac{f_2 \; f_3}{f_2 + f_3 - L_{23}} \xrightarrow{f_2 \to \infty} f_3$$



Folded Design - C
f3 31.79 m
Gouy phase shift 20.0 degree
Rayleigh range 0.27372 m
waist size 31.93257 mm
ROC at PRM 0.83484 m
beam radius at PRM 0.87 mm
beam radius at z=14.1 19.84 mm
PRM3
f_3=31.79
PRM2
flat mirror
PRM
ROC = 0.835 m
w (mm)
z (m)
0
5
10
15
20
25
30
35
40
-40
-30
-20
-10
0
10
20
30
40



Folded Design - C
$f_2 = \infty, f_3 = +31.79$
mode mis-match
1e-02
1e-03
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
-30
-25
-20
-15
-10
-5
0
5
10
15
telescope length (mm)
Nominal
f3 -0.05%
31.79 * -0.05%
= 15.9 mm

Telescope Optimization

Design	f_2	f_3	F	Tolerances length (mismatch=1e-4)	 f_3	 f_2
I	-1.95	+16.0	+624	3.0 mm	0.06%	0.5%
II	-4.74	+18.0	+102	3.5 mm	0.06%	0.15%
III	-0.81	+15.0	-135	2.5 mm	0.07%	0.8%
C		+31.79	+32	10 mm	0.03%	-----

ここまでのまとめ

レンズ２枚の合成 focal length (F) を指標に、幾つかの telescope 設計における許容値 (tolerance) を調べてみた結果。

F を小さくすれば、レンズ間距離に対する許容値は若干大きくなるが、反面 f_3 に対する許容値が小さくなることが分かった。

しかし、一番重要なことはこれらは程度問題の話で telescope の設計を変えても許容値のオーダーは変わらず、telescope の設計が非常に厳しいことに変わりはなかった。次節以降では別の観点から最適な telescope 設計について考察する。

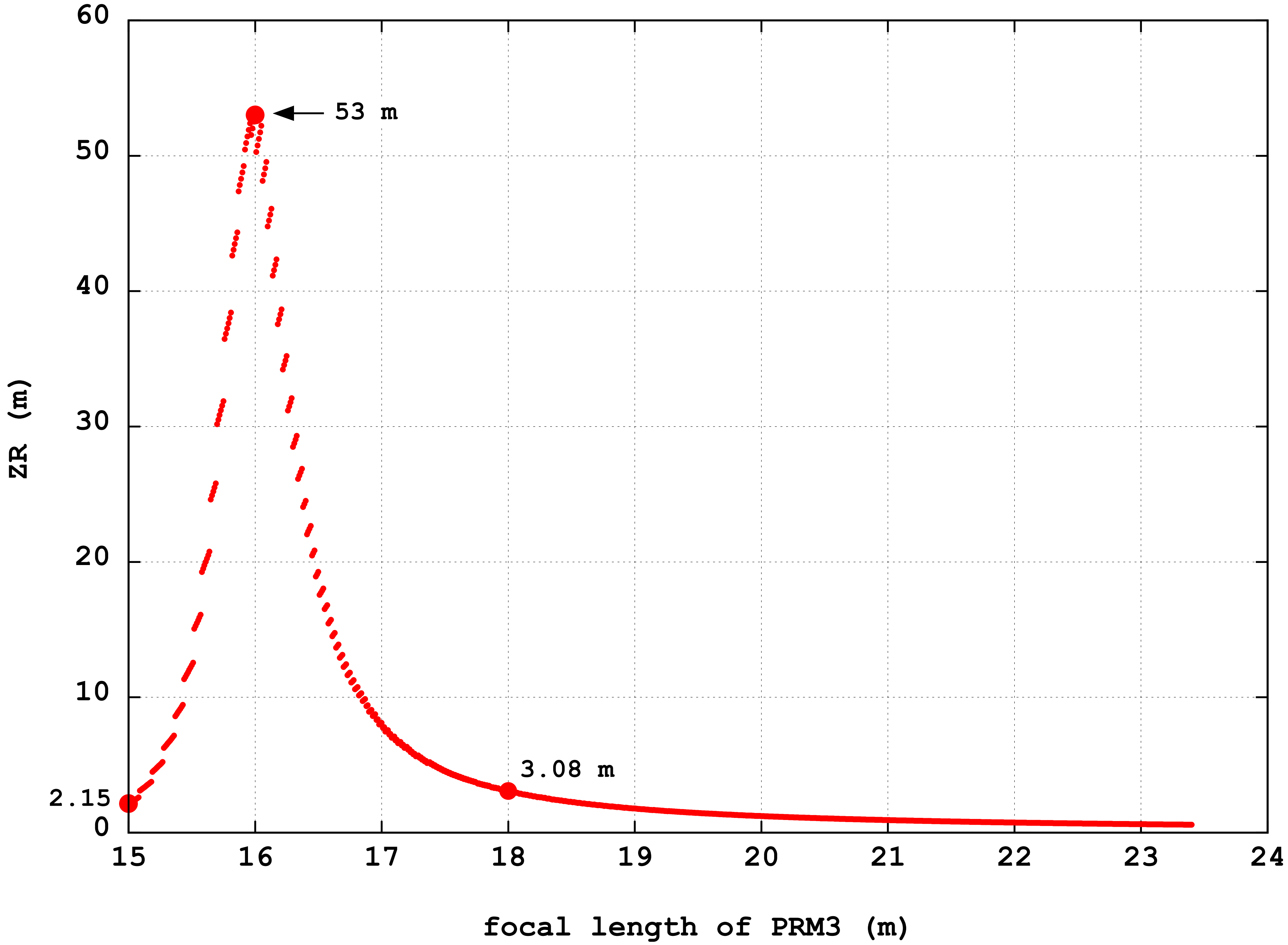
Input beam profile from the 2nd Mode Cleaner

ここでは、telescope の最適設計を考えるために telescope への
入射 (SRC 側は出射) beam profile (主に Rayleigh range) について評価した。

評価の結果、**f3 = +16.0 m において Rayleigh range (ZR) が最大**となる。
Rayleigh range が大きいことのメリット

o 干渉計の組み立て工程で、**PRM がなくても** mode mismatch への
影響が少ない。(PRM の曲率半径が大きいことも効いているが)

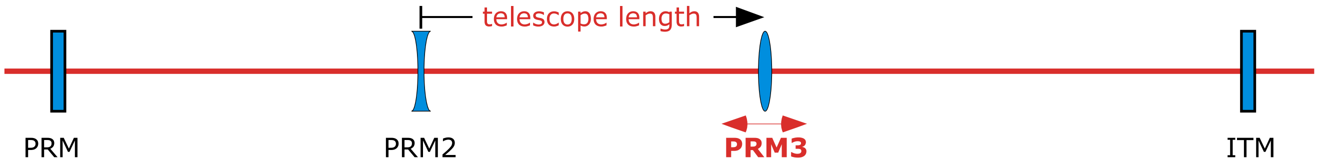
o 入射パワー増加に伴い**熱レンズ効果**が増大した場合、telescope 長を調整
しても入射ビームとの mode mismatch の影響が小さい。



53 m
3.08 m
2.15
ZR (m)
focal length of PRM3 (m)
0
10
20
30
40
50
60
15
16
17
18
19
20
21
22
23
24

Telescope の調整方法の考察

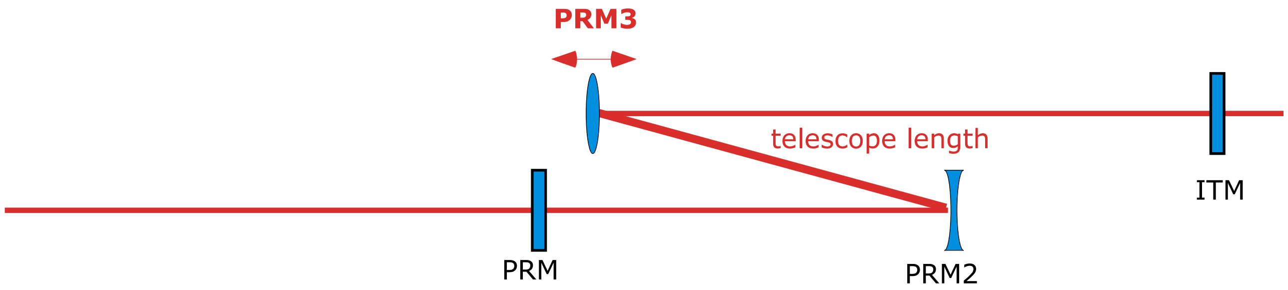
(1.1) linear arrangement



The resonated arm cavity has a beam profile with Rayleigh range of 2904 m.
Therefore, mode matching is insensitive for small change of PRM3 lens position.
It is the easiest way for adjusting telescope length to **relocate only PRM3 lens**.
In this report, all of telescope length changes are adopted this way.
Here the relocation means position change of larger than 10 mm.

**** Order of relocation**
In the case of that focal length of PRM3 is 16 m and its error is 1%,
the relocation is 16 x 1.0e-2 = 0.16 m = 160 mm.

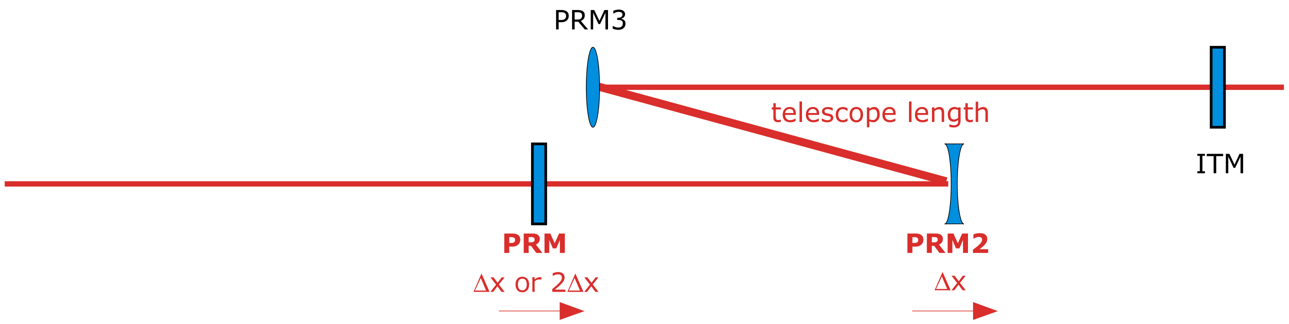
(1.2) folded arrangement



In the folded design, a relocation of PRM3 causes not only telescope length change but also PRC length change. If small change of PRC length is negligible, only relocation of PRM3 lens is the best solution.

Telescope の調整方法の考察

(2.1) PRM3 is fixed in folded arrangement

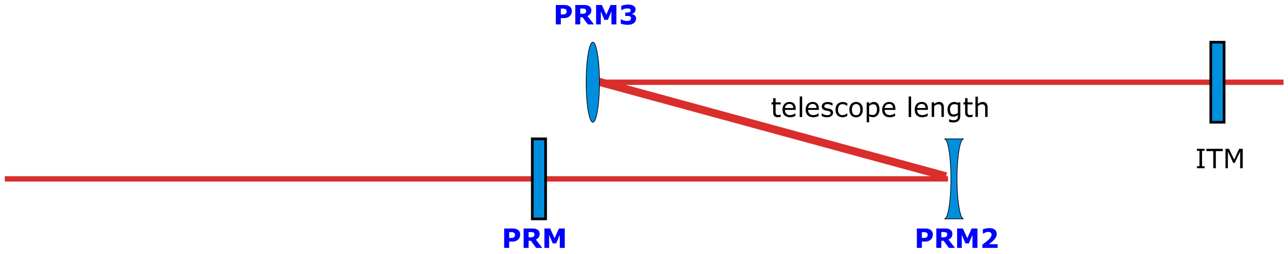


Because PRM3 lens has same dimensions of ITM mirror of 250 mm diameter,
PRM3 needs large suspension system. In the view of seismic attenuator,
it is hard to relocate PRM3.

If so, there is two possibilities. One is common relocation of PRM and PRM2.
This has a demerit of PRC length change.
The other is to relocate PRM with twice displacement of PRM2.
This has a demerit of additional mode mismatch due to a length change between
PRM and PRM2.

Telescope の調整方法の考察

(3) Adjustment of lens focal length



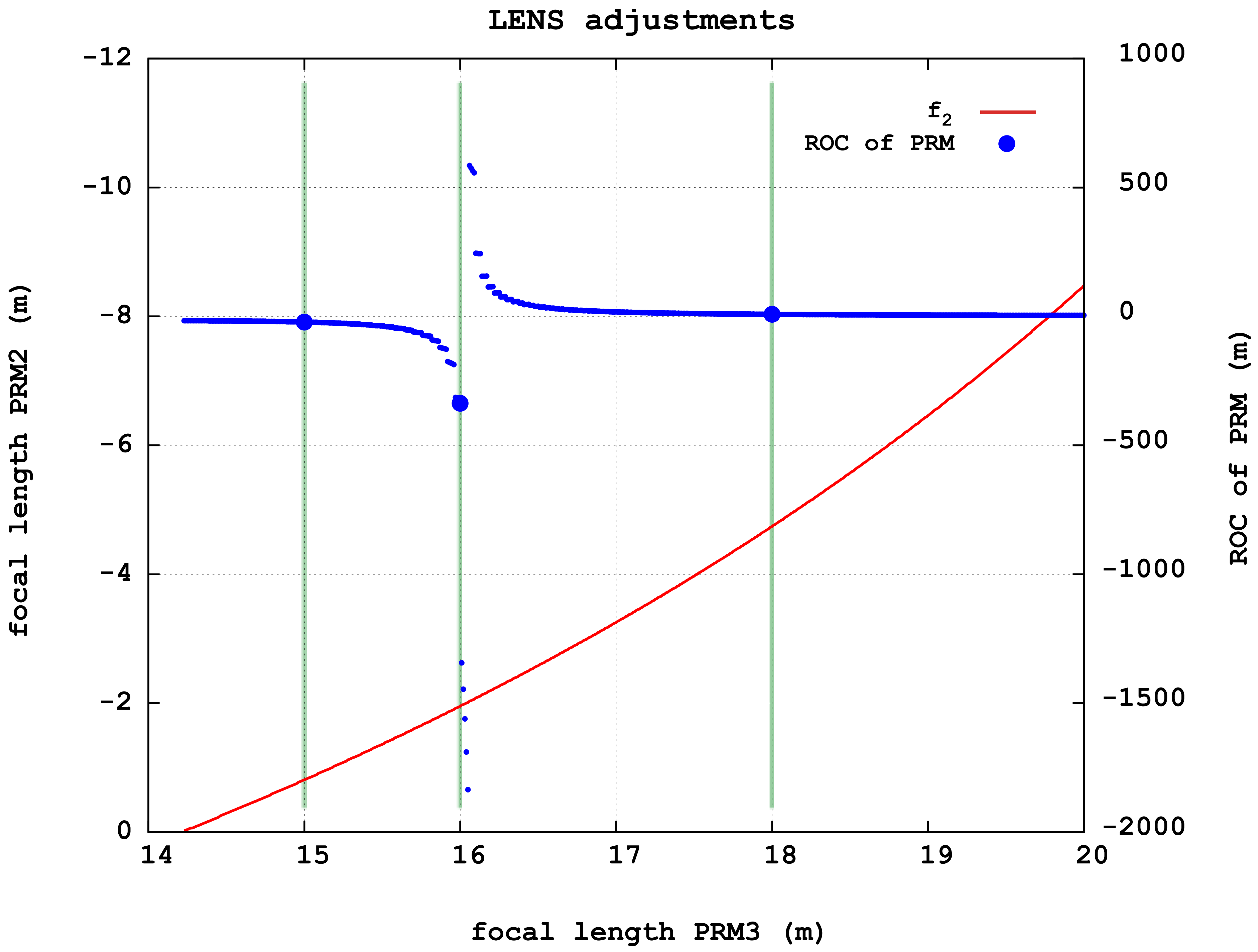
As mentioned before, lens relocations have several problems.
Here let consider the way of lens adjustments.

Among the three optical components of PRM, PRM2 and PRM3,
a requirement for PRM3 is the most critical.
Therefore, the following procedure is considered.

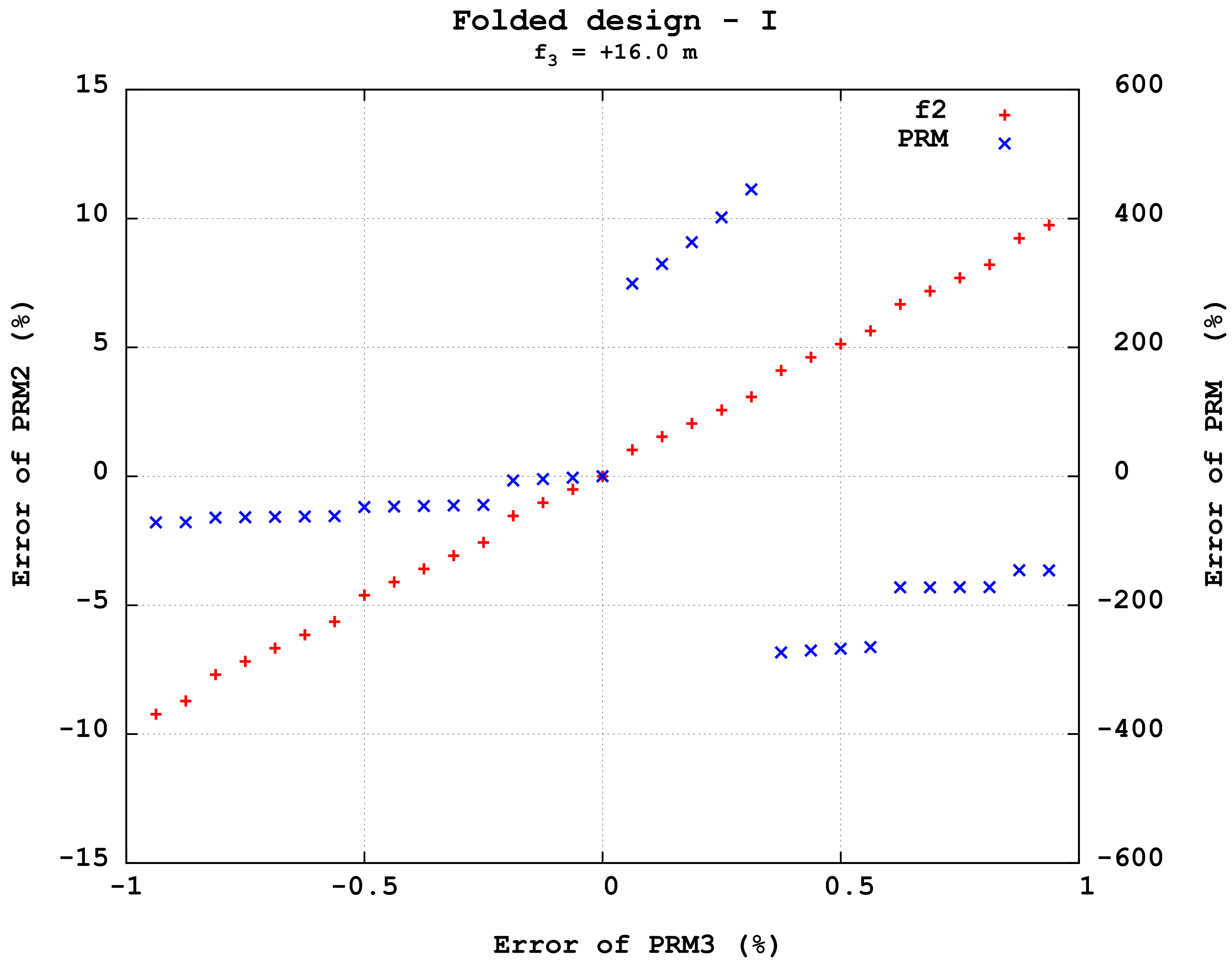
(1) First of all, the PRM3 lens is polished within 1% error.
Then, the focal length is measured.

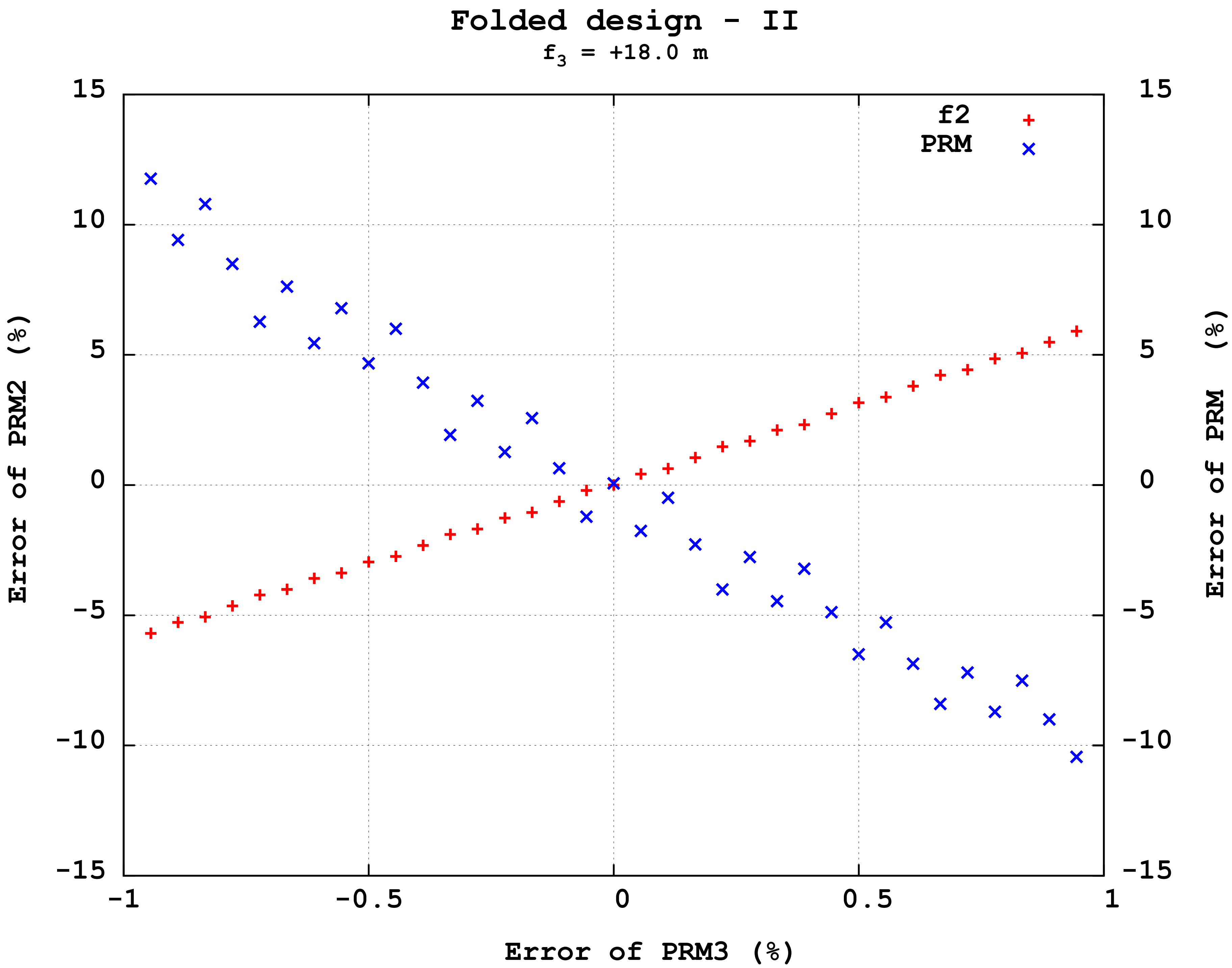
(2) Based on measured PRM3 focal length, focal length of PRM2 and
of PRM are designed and then are ordered with 0.5% and 1% error, respectively.

(3) Finally fine adjustment of lens position will be performed.

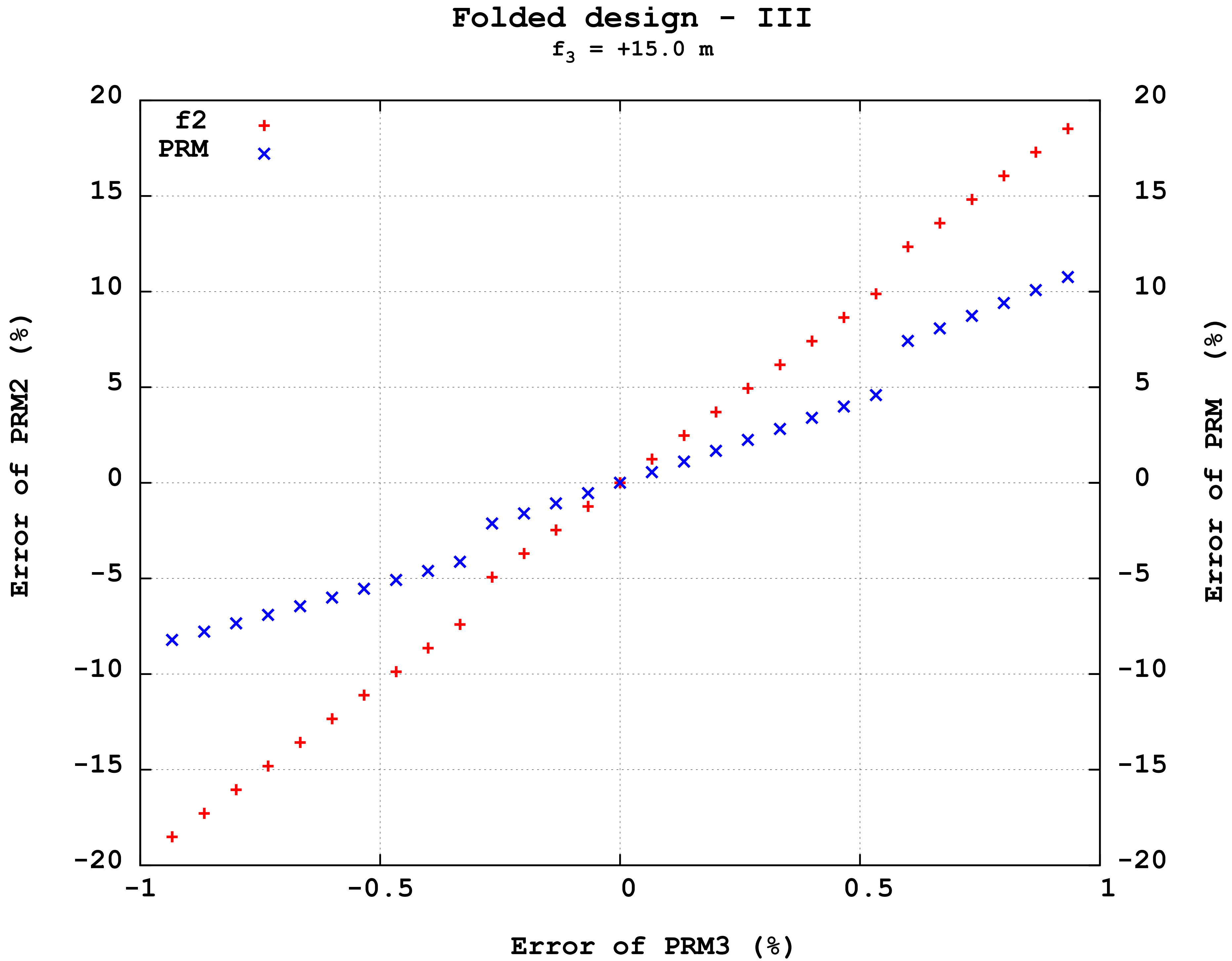


LENS adjustments
-12
-10
-8
-6
-4
-2
0
14
15
16
17
18
19
20
1000
500
0
-500
-1000
-1500
-2000
f_2
ROC of PRM
focal length PRM2 (m)
ROC of PRM (m)
focal length PRM3 (m)


Folded design - I
f3 = +16.0 m
f2
PRM
Error of PRM2 (%)
Error of PRM (%)
Error of PRM3 (%)
15
10
5
0
-5
-10
-15
600
400
200
0
-200
-400
-600
-1
-0.5
0
0.5
1



Folded design - II
f_3 = +18.0 m
f2
PRM
Error of PRM2 (%)
Error of PRM (%)
Error of PRM3 (%)
15
10
5
0
-5
-10
-15
-1
-0.5
0
0.5
1


Folded design - III
f_3 = +15.0 m
f2
PRM
Error of PRM2 (%)
Error of PRM (%)
Error of PRM3 (%)
20
15
10
5
0
-5
-10
-15
-20
-1
-0.5
0
0.5
1

Telescope の調整方法の考察

(3) Adjustment of lens focal length

summary of results

Design	Comments
I	PRM is very sensitive for both PRM2 and PRM3. It will be **impossible** to adjust with this procedure.
II	It will be **possible**, if focal length of PRM3 can be measured less than 0.1% accuracy.
III	Same as for design II