Reduction of Atmospheric Modelling Errors Using Multiple Wavelength Ranging

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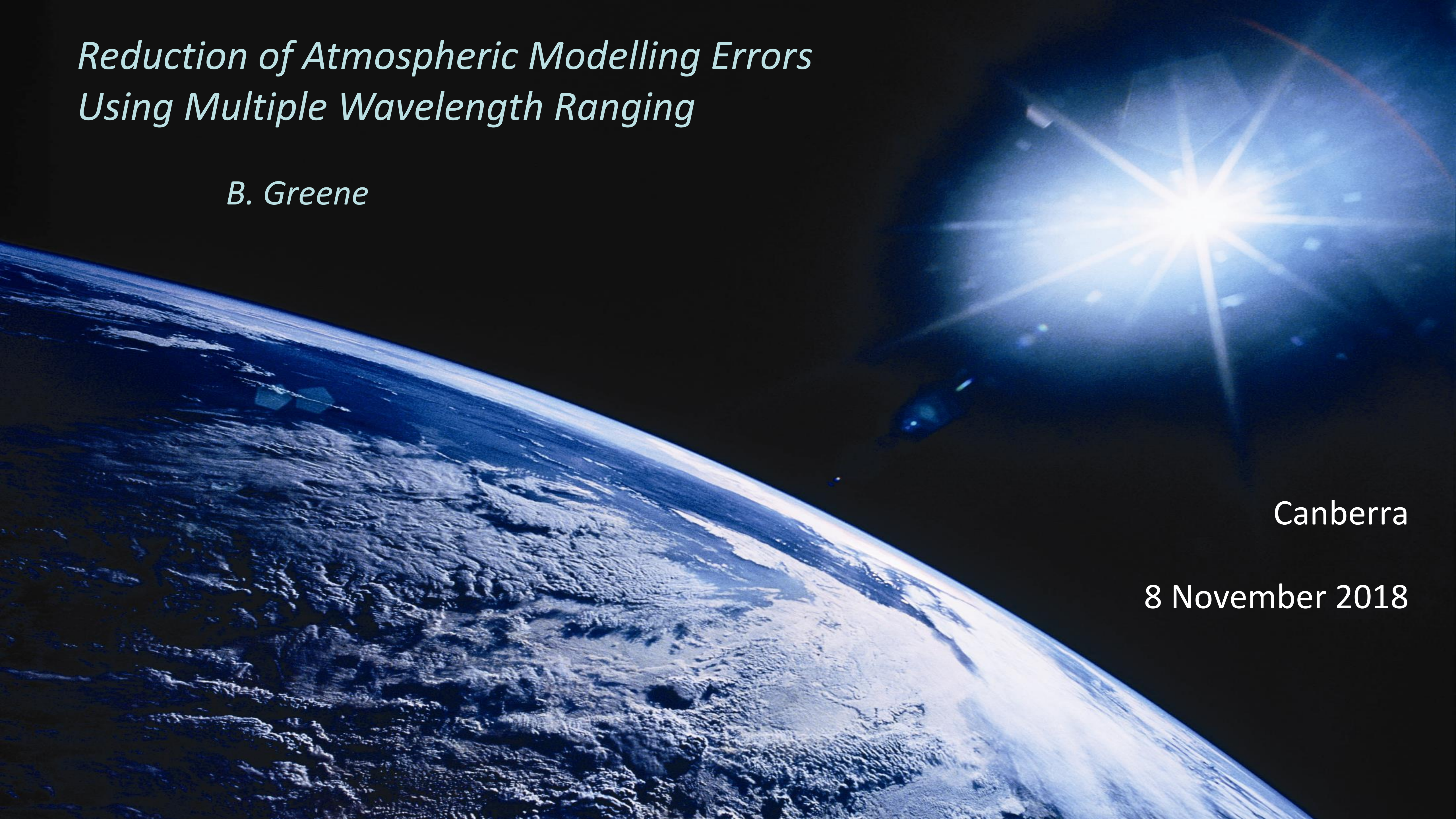
8 November 2018



References:

1. **Greene & Herring**: "Multiple Wavelength Laser Ranging", Proc. 6th Laser Ranging Workshop, Antibes – Juan les Pins, Vol. 2 (1986), p.581 ff.

2. **Degnan**: "Millimeter Accuracy Satellite Laser Ranging: A Review", Contributions to Space Geodesy to Geodynamics: Technology, AGU Geodynamics Series Vol. 25 ("the red book") (1993), pp. 147-150.

3. **Wijaya & Brunner**: "Accurate atmospheric correction of two-frequency SLR observations", Proc.16th Laser Ranging Workshop, Poznan, Vol. 1 (2008), esp. p 132.

A large proportion of the underlying literature is based on research performed 60 years ago…..

Background

1. By 1986 it was clear that measuring range difference at multiple wavelengths on a shot-by-shot basis would not deliver accuracy. [Major contributions by Gagnebet et al, Hamal et al].
2. By 1986 it was also clear that a <2 ps systematic error floor was achievable for emerging epoch timing systems and SPE receivers. This opened the way for NP precision of 2 ps for each individual wavelength used for 2-color correction.
3. In 1986 Greene and Herring proposed the "*difference of normal points*" rather than the "*normal point of differences*" be used as the basis for atmospheric correction of SLR data. All current atmospheric correction schema follow this format.
4. ITRF requirements for crucial applications from 2020 and beyond will require new levels of precision and accuracy. A combination of RF and ***optical techniques including atmospheric correction*** will be needed.

Sensitivity

If range measurements R_1, R_2 are made independently (no covariance) with variances σ_1^2, σ_2^2, then the RMS σ_S (variance of the vacuum distance) is:

$$\sigma_S = \sqrt{v_2^2\sigma_1^2 + v_1^2\sigma_2^2}$$

where v_1 & v_2 are the sensitivities for the specific wavelengths used.

Wavelenght Pair		Greene & Herring		Degnan		Indicative
λ_1 [nm]	λ_2 [nm]	V_1	V_2	V_1	V_2	V_{AVGE}
1547	355	8.0	7.0	8.1	7.1	**7.5**
1064	532	22.3	21.3	22.2	21.2	**21.8**
1064	355	8.4	7.4	8.6	7.6	**8.0**
1547	532	19.1	18.1	19.0	18.0	**18.6**
532	355	13.0	12.0	13.3	12.3	**12.6**
1547	1064	127.1	126.1	127.9	126.9	**127.0**

Measurements in each wavelength must be made with 7-127 times greater precision than the accuracy required.

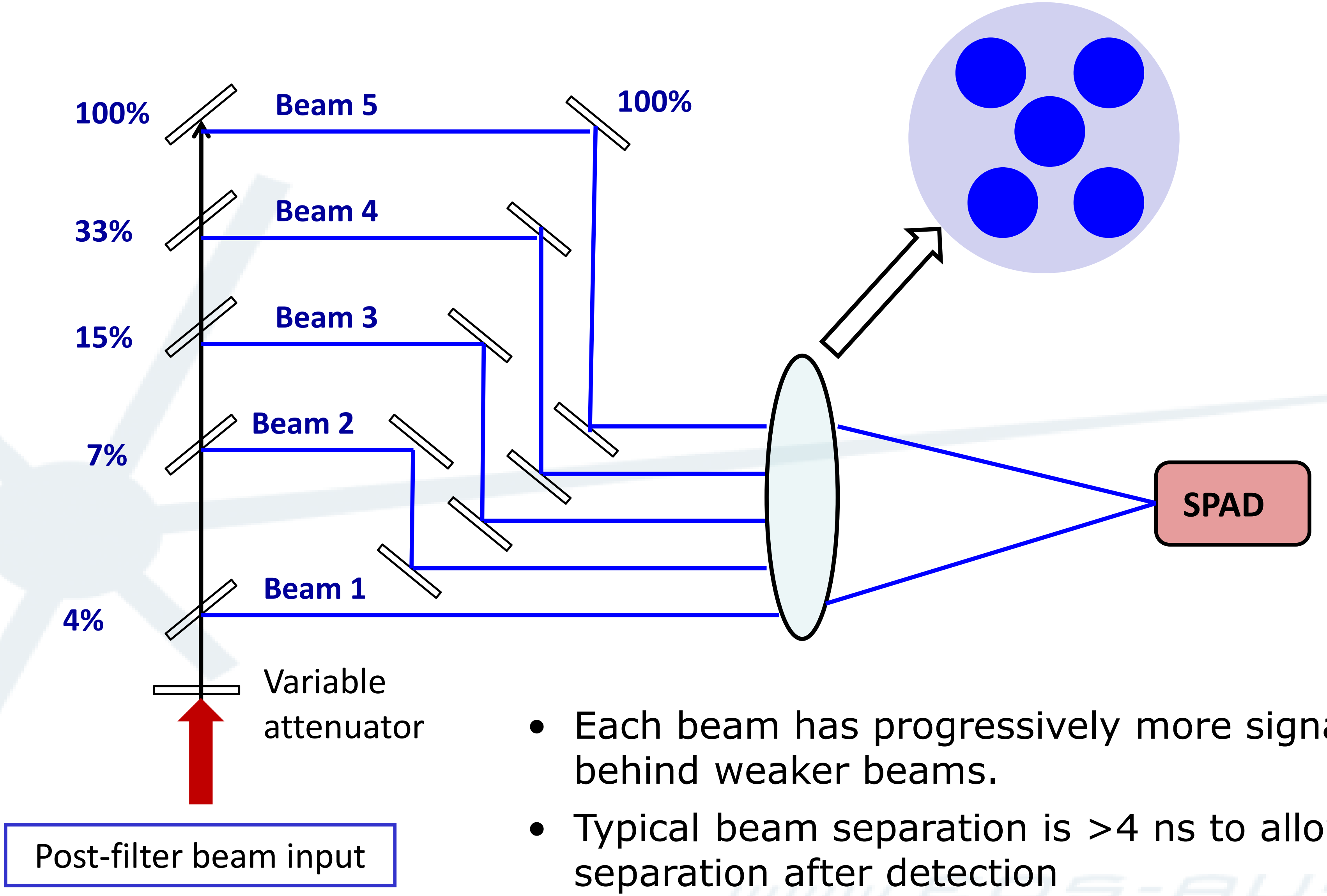
Sensitivity

Normal point precision required to achieve **5 mm** range correction:

λ_1 [nm]	λ_2 [nm]	V	NP [mm]	NP [ps]
1547	355	7.5	0.5	3.1
1064	532	21.8	0.2	1.1
1064	355	8.0	0.4	2.9
1547	532	18.6	0.2	1.3
532	355	12.6	0.3	1.9

1. Key elements are NP precision of <2 ps and a bias **error floor** <2 ps.
2. This can only be achieved with SPE receivers with “zero” dynamic range
3. However SPE receivers run at 10% return rate to control bias

SPE Receiver: 1-wavelength channel shown



- Each beam has progressively more signal, and falls behind weaker beams.
- Typical beam separation is >4 ns to allow easy separation after detection

Detector Module Data

	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5
Split Ratio	4%	7%	15%	33%	100%

Photons received	PHOTONS					PHOTOELECTRONS				
	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5
10,000	350	676	1346	2517	5111	7	14	27	50	102
5,000	175	338	673	1259	2555	4	7	13	25	51
2,500	88	169	337	629	1278	2	3	7	13	26
1,250	44	84	168	315	639	1	2	3	6	13
625	22	42	84	157	319	0	1	2	3	6
313	11	21	42	79	160	0	0	1	2	3
156	5	11	21	39	80	0	0	0	1	2
78	3	5	11	20	40	0	0	0	0	1
39	1	3	5	10	20	0	0	0	0	0
20	1	1	3	5	10	0	0	0	0	0
10	0	1	1	2	5	0	0	0	0	0
5	0	0	1	1	2	0	0	0	0	0

Any beam with signal when leading beams have none will be SPE

Detector Module Data

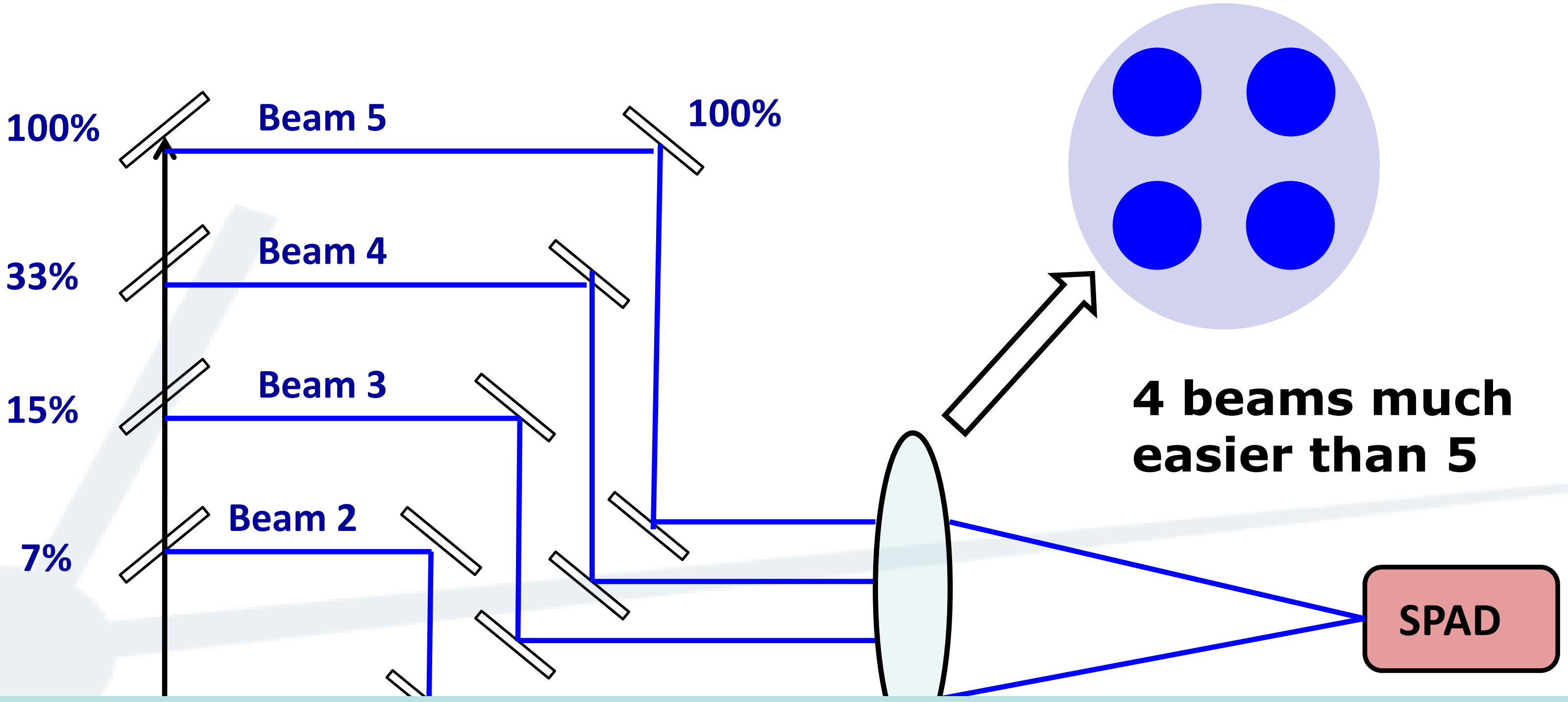
Beam 1 signal cannot be used

Photons received	PHOTONS					PHOTOELECTRONS				
	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5
10,000	350	676	1346	2517	5111	7	14	27	50	102
5,000	175	338	673	1259	2555	4	7	13	25	51
2,500	88	169	337	629	1278	2	3	7	13	26
1,250	44	84	168	315	639	**1**	2	3	6	13
625	22	42	84	157	319	0	**1**	2	3	6
313	11	21	42	79	160	0	0	**1**	2	3
156	5	11	21	39	80	0	0	0	**1**	2
78	3	5	11	20	40	0	0	0	0	**1**
39	1	3	5	10	20	0	0	0	0	0
20	1	1	3	5	10	0	0	0	0	0
10	0	1	1	2	5	0	0	0	0	0
5	0	0	1	1	2	0	0	0	0	0

Dynamic range is about x8, *almost* matching the atmospheric signal modulation.

This receiver essentially tracks the signal to hold SPE domain.

Simplified SPE Receiver



In practice:

1. Signal dynamic range is still too large - still only 30-50% return rate
2. UV channel is consistently under-performing

ll

anyway

Post-filter beam input

Normal Point Precision

λ [nm]	PW (ps)	Laser rate	Energy (mJ)
1547	9	100	2
1064	11	100	2
532	9	100	2
355	8	100	2

λ [nm]	NP Period	Laser rate	QE @ λ	Ret Rate λ	Returns
1547	60	100	20%	50%	**3,000**
1064	60	100	3%	30%	**1,800**
532	60	100	20%	50%	**3,000**
355	60	100	3%	30%	**1,800**

λ [nm]	Returns	"q" factor	RMS λ2 (mm)	NP RMS (mm)	NP RMS (ps)
1547	3,000	1.6	10	0.29	**1.9**
1064	1,800	1.6	10	0.38	**2.5**
532	3,000	1.6	10	0.29	**1.9**
355	1,800	1.6	10	0.38	**2.5**

The system error floor is around 2 picoseconds RMS

Corrected NP Range to 3 mm RMS

λ1 [nm]	λ2 [nm]	V_1	V_2	RMS λ1	RMS λ2	Corr Range [mm]
1547	355	7.96	6.96	0.29	0.38	**3.51**
1064	532	22.27	21.27	0.38	0.29	**10.45**
1064	355	8.43	7.43	0.38	0.38	**4.24**
1547	532	19.08	18.08	0.29	0.29	**7.68**
532	355	12.95	11.95	0.29	0.38	**5.88**

With current devices the corrected range precision can be **3-10 mm** for 1 minute arcs, depending on the wavelengths applied.

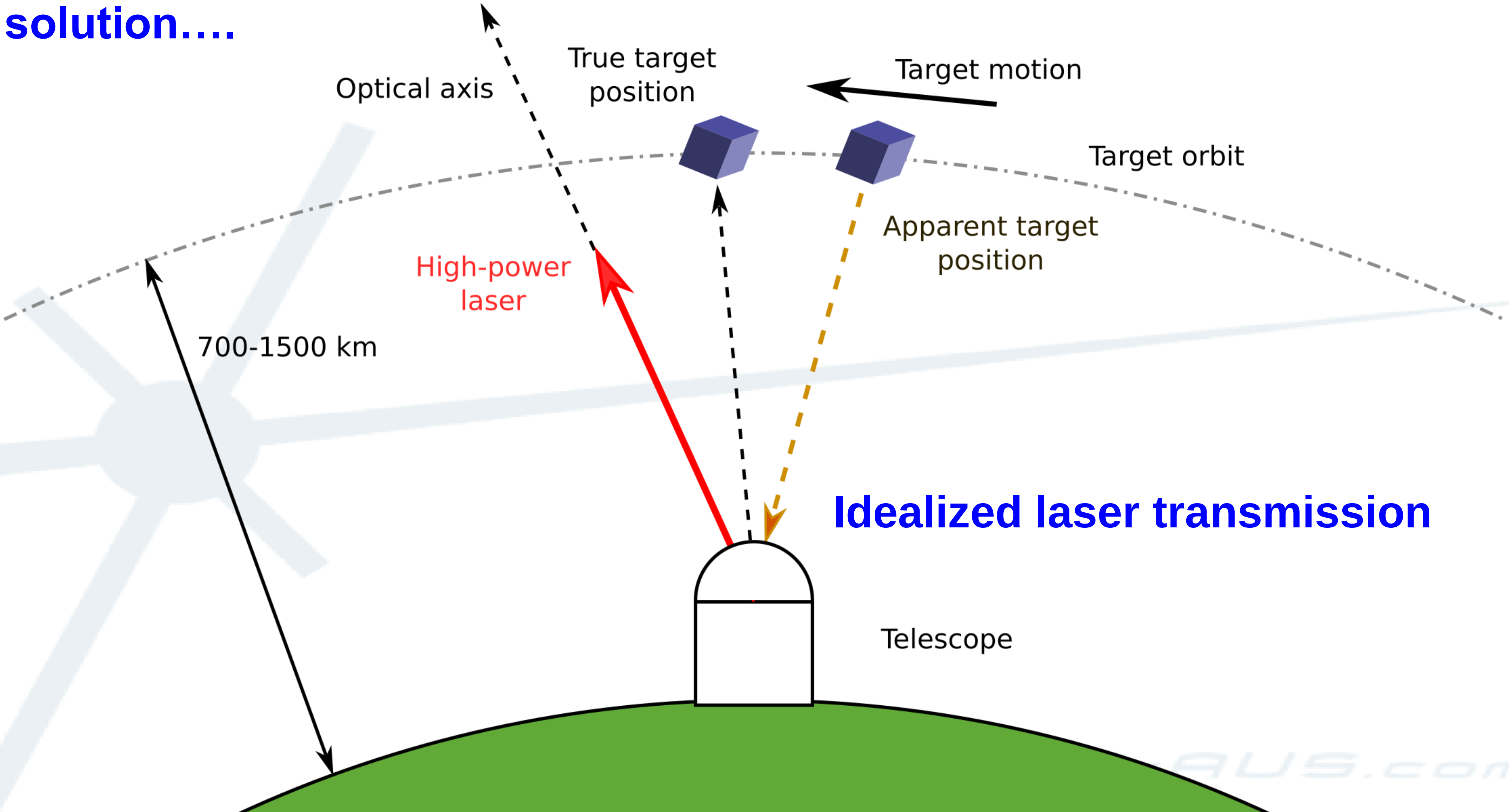
Survey marks and site surveys require attention before this level can be improved.

Current technology and separate, simultaneous 2-color measurements [4-5 colour pairs] can be used to further reduce the formal error of the range correction to below **3 mm RMS**.

Improvements……….

A key issue is the tradeoff between optical complexity, optimizing the return rate, UV signal strength, and the signal dynamic range imposed by the atmosphere.

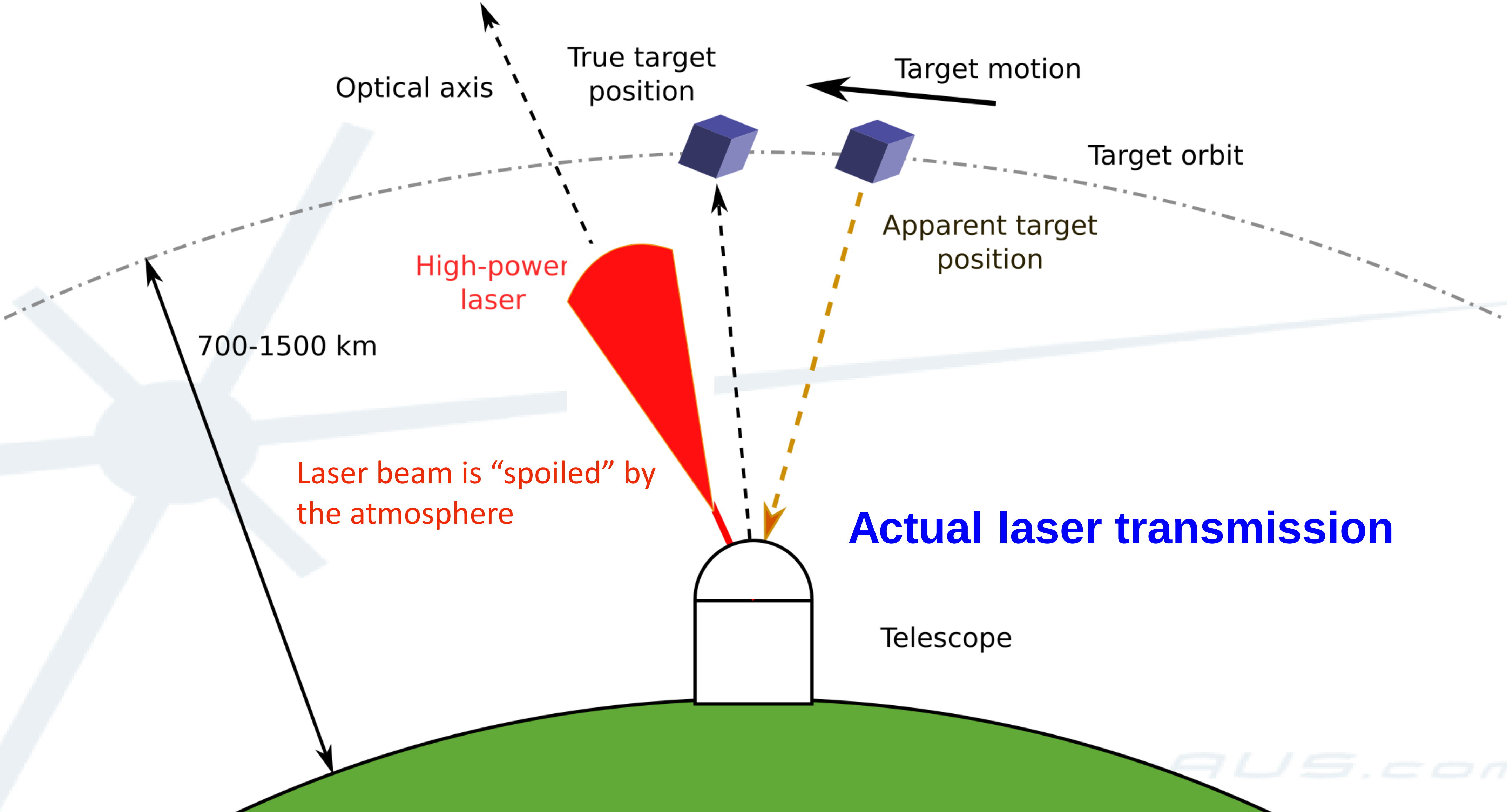
One solution….



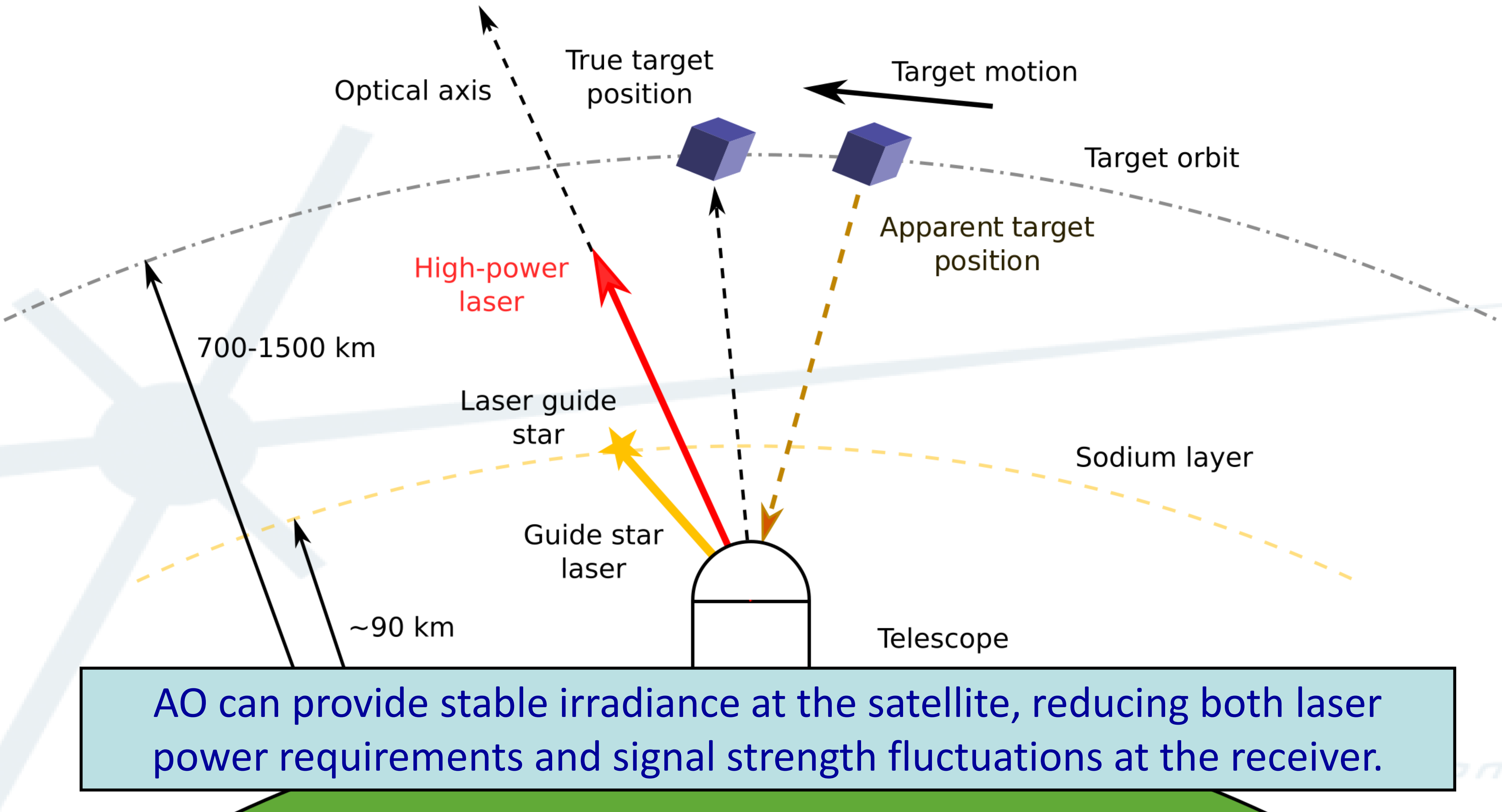
Idealized laser transmission

Actual laser transmission

We measure x10 irradiance variations in space, and beam divergence > 15 urad PTP



Adaptive Optics Solution



AO can provide stable irradiance at the satellite, reducing both laser power requirements and signal strength fluctuations at the receiver.

How to achieve 1 mm Accuracy…

1. Increase data rate x2 with higher laser rate [200+ Hz]
2. Reduce signal strength dynamic range using adaptive optics, > 80% return rate at SPE
3. Reduce detector jitter 20% by device selection and improved cooling

λ1 [nm]	λ2 [nm]	V_1	V_2	RMS λ1	RMS λ2	Corr Range [mm]
1547	355	7.96	6.96	0.15	0.19	**1.75**
1064	532	22.27	21.27	0.19	0.15	**5.22**
1064	355	8.43	7.43	0.19	0.19	**2.12**
1547	532	19.08	18.08	0.15	0.15	**3.84**
532	355	12.95	11.95	0.15	0.19	**2.94**

1. NP precision of ***2-5 mm*** for 1 minute arcs can be achieved for all wavelength pairs.
2. Higher [kHz] laser rates may not help because we are at the 2 ps bias error floor.
3. Separate, simultaneous 2-color measurements reduce the formal error to **1mm RMS**.
4. Long data spans will ultimately reduce the error floor to around 1 ps or <**0.2 mm**

Conclusions

1. 3 mm range correction is now feasible
2. 1 mm range correction within reach
3. GGOS objective of 0.1 mm should be achievable