Multiple Wavelength Correction for Atmospheric Refraction

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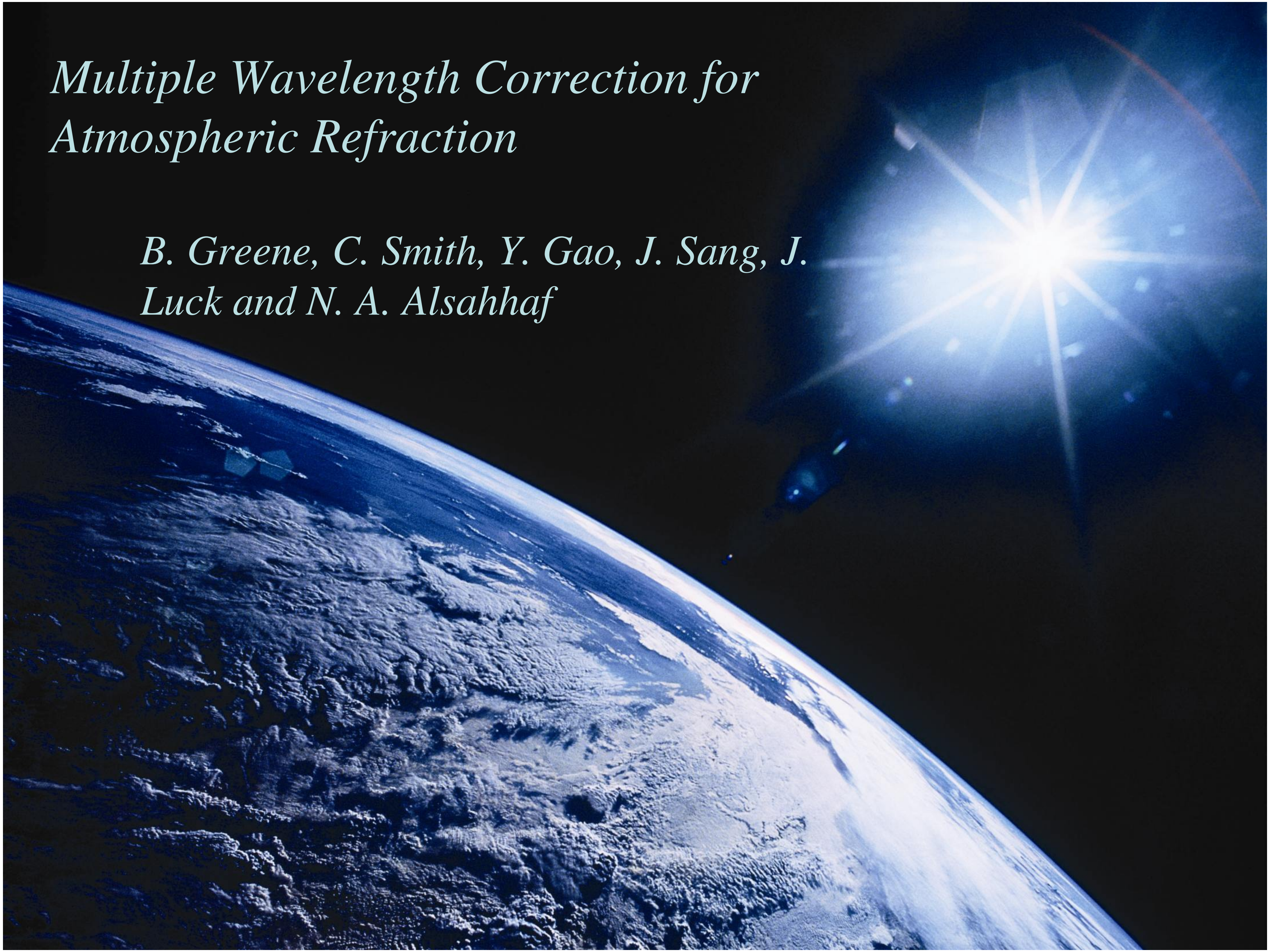


Abstract

We describe a system to determine the atmospheric refraction correction to **<3 mm** using current-generation physical devices, and **<1 mm** with incremental improvements.

Background

1. By 1986 it was clear that measuring range difference on a shot-by-shot basis would not deliver. [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. 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.

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 required in the corrected range measurement.

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

The key elements are NP precision of <2 ps and suppression of the error floor <2 ps.

Key Issues Since 1986

Dual objectives of <2 ps NP precision <u>and</u> <2 ps systematic error have proven elusive because:

1. **Data links below 450 nm are weak:**

   Link budgets have proven too low to produce sufficient data for blue-UV normal points, especially at low elevations.

2. **SPE operation required:**

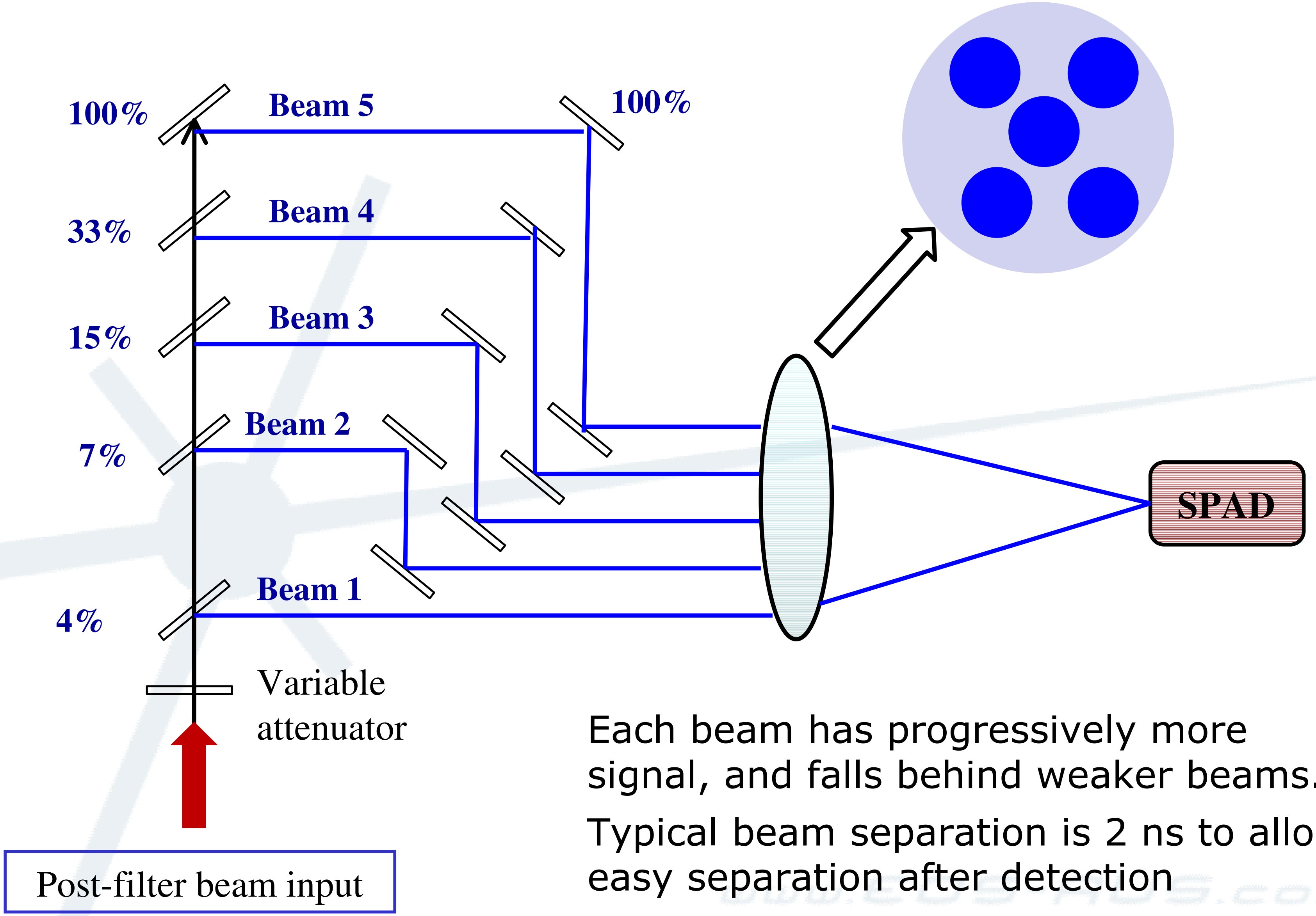
   The principal limitation is that the only known detector with bias <<2ps is the SPAD, which must be constrained to SPE operation to meet this limit. SPE operation is assured for range return rates below [about] 10% and this conflicts with the range data rate requirements to achieve <2 ps NP precision.

Solutions:

1. **Telescope quality**
2. **Adaptive optics**
3. **Laser power**
4. **SPE SPAD Receiver**

<u>Here we deal only with SPE receiver design</u>

SPE Receiver Concept



Each beam has progressively more signal, and falls behind weaker beams.

Typical beam separation is 2 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

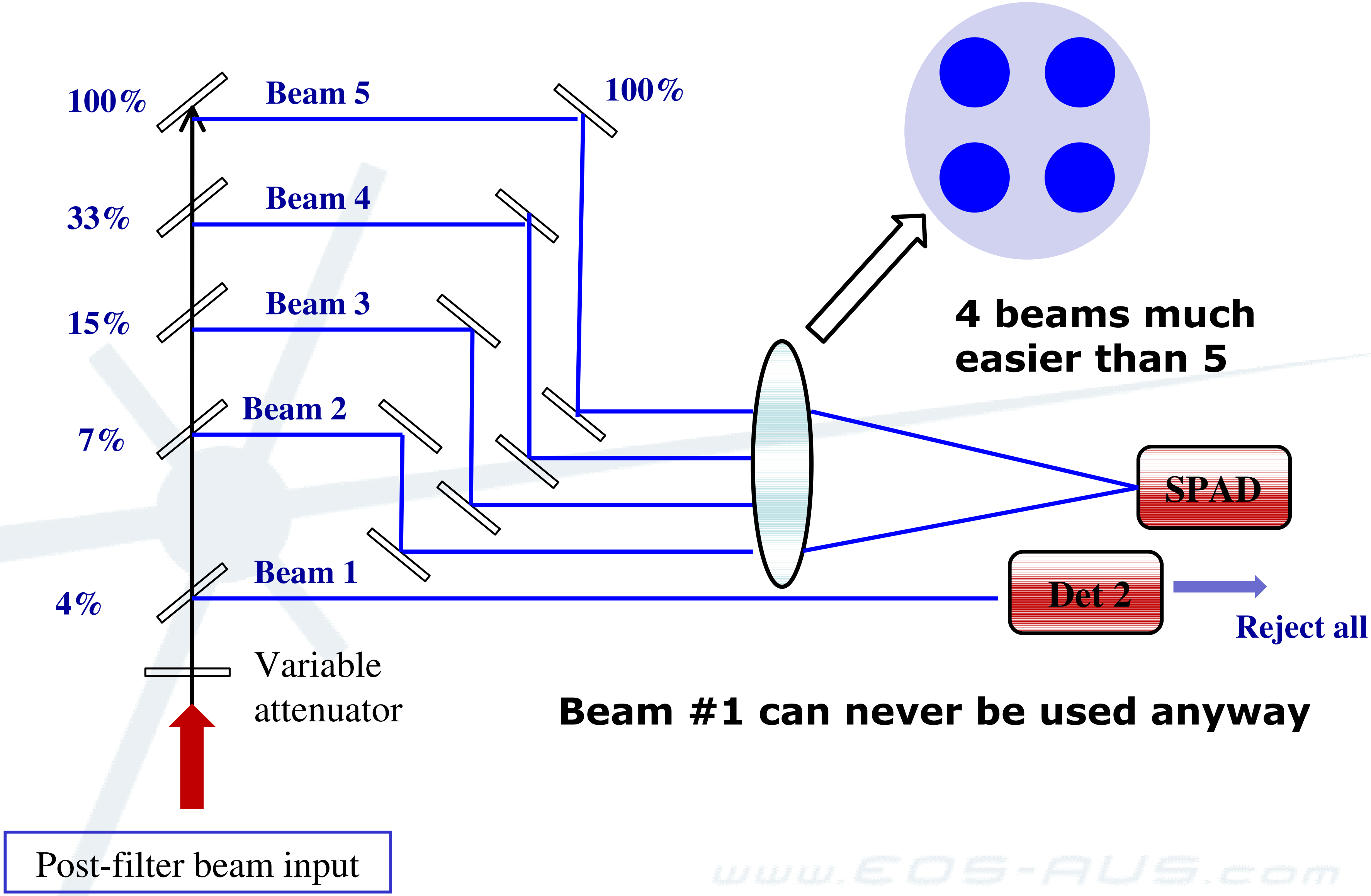
EOS

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 of the receiver is 1-16 photoelectrons SPE, matching the atmospheric signal modulation. The receiver can track the signal with proportional response, instead of binary response, to hold SPE domain.

Simplified SPE Receiver



4 beams much easier than 5

Beam #1 can never be used anyway

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 Range Precision

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 will be 3-10 mm for 1 minute arcs, depending on the wavelengths applied.

Separate, simultaneous 2-color measurements [up to 5] can be used to further reduce the formal error of the range correction to below **3 mm RMS**.

Further Improvements

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**

For ***400Hz*** *laser* and ***8 mm*** SPAD in SPE, the corrected range precision will be 2-5 mm for 1 minute arcs, depending on the wavelengths applied. Higher laser rates will not help.

Separate, simultaneous 2-color measurements [up to 5] can be used to further reduce the formal error of the range correction to **1mm RMS**.

Why 100Hz

1. Sufficient energy available on all 4 wavelengths
2. Fast enough to track atmosphere [100Hz]
3. Avoids ps timing bias for kHz rep rates
4. Matches attenuator bandwidth [100 Hz] in receiver
5. Allows multiple wavelength mono-static transmit-receive configurations [mechanical]

New Issues

1. **Beam divergence in receiver:**

   Works best for smaller [<100cm] telescopes.

2. **Beam and coating complexity:**

   Transmit configuration is complex for 5 wavelength output [if 589nm is used]

Conclusions

1. **3mm range correction is now feasible**
2. **1mm range correction within reach**

Conclusions

1. **3mm range correction is now feasible**
2. **1mm range correction within reach**
3. **25 years passes quickly in SLR**

Bibliography

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.