LLR in IR

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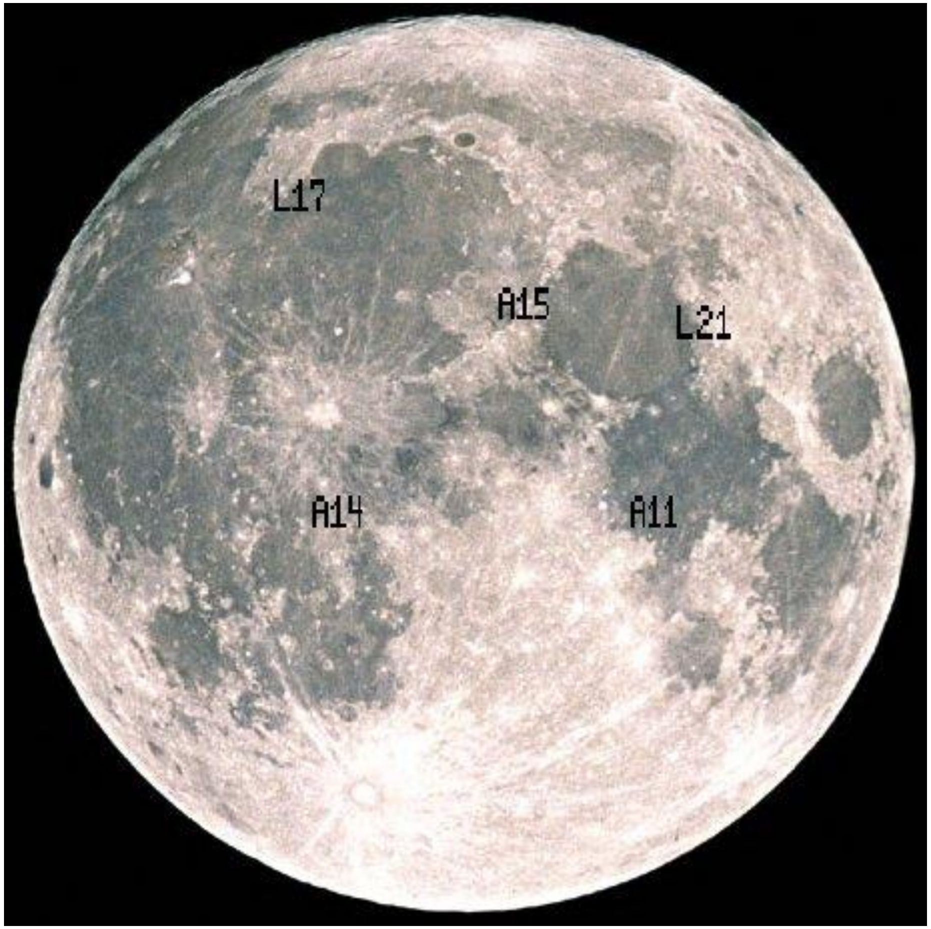
October 2016 – Potsdam
20th ILRS Workshop

Scientific context

- LLR uses 5 retro-reflectors placed on the moon



Inhomogeneous LLR observations

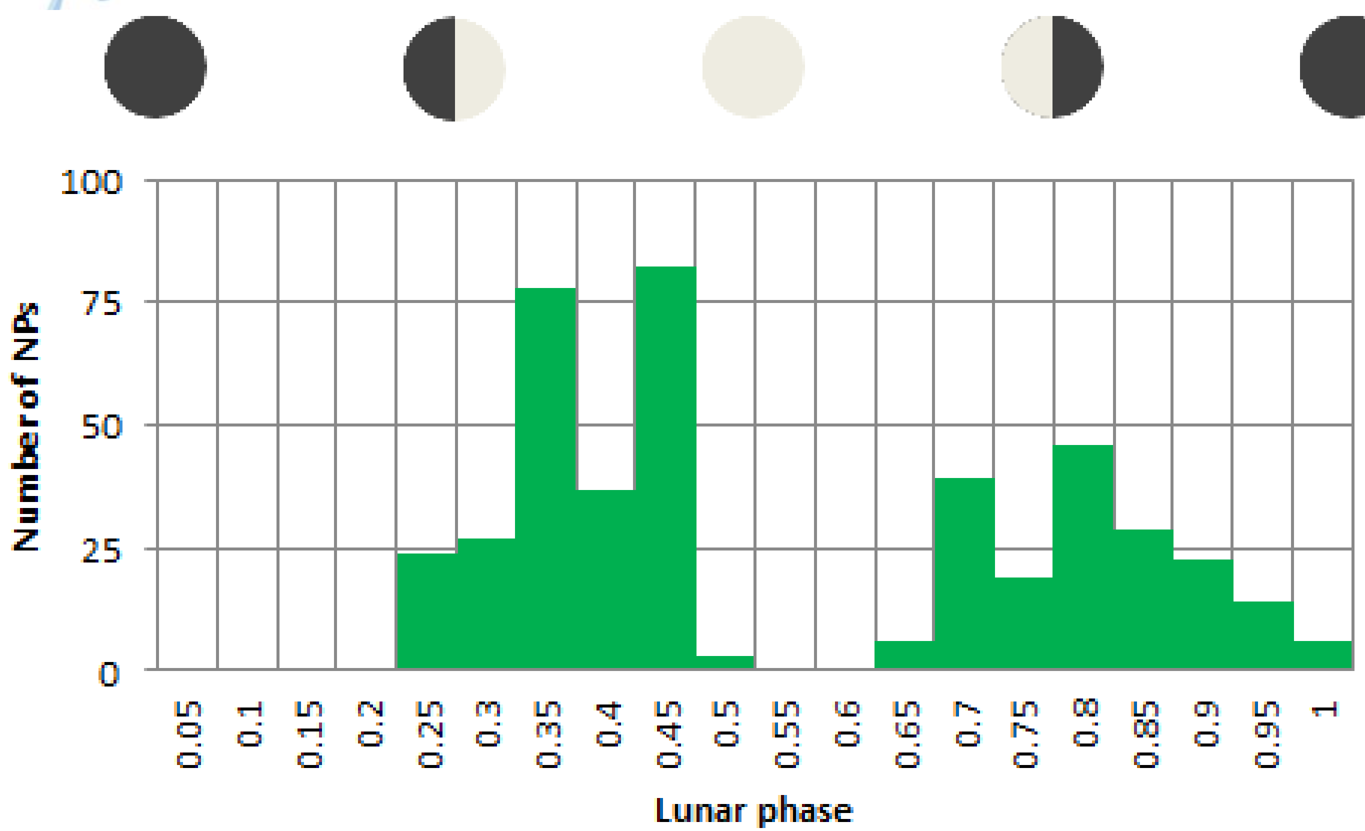


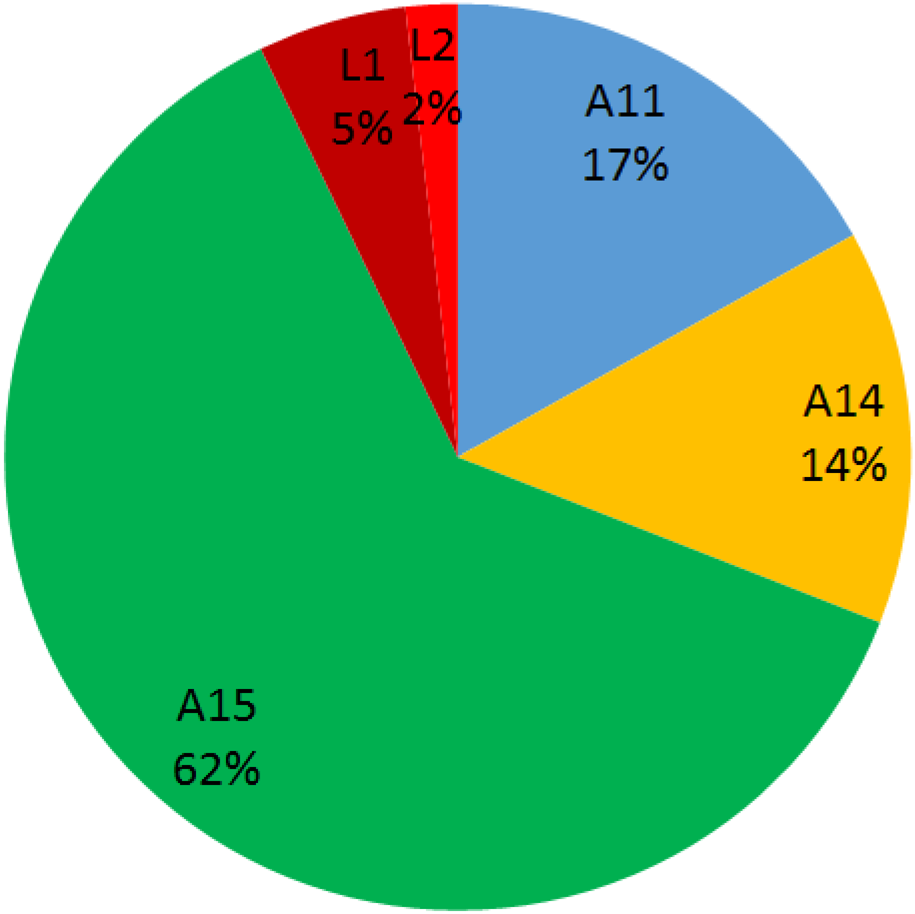
Fig. 1. Number of NPs in 2014, **from Grasse only,** versus the lunar phase. All the observations have been done with the green wavelength. **New moon is depicted by a dark disk and matchs Lunar phase 0.0. Full moon is depicted by a bright disk and matchs lunar phase 0.5.**

- New moon: Surface of the moon is not visible ; high background noise hidding many echoes
- Full moon: high background noise

Inhomogeneous LLR observations

Fig. 2. Distribution of the NP on the different lunar retro-reflectors during the year 2014 with green beam at the Grasse LLR station

Low S/N and link budget
=>
most of the observations are done on A15, the largest retro-reflector



LLR data production is inhomogeneous both in time and in the retro-reflectors observed

IR SPAD for LLR

- Objectives of instrumental developments

  Increase the number of measurements close to the new and full moon periods

  => improvement of the S/N

- Why choosing IR ?
  - For the same energy, two times more photons in IR than in green
  - More energy without second harmonic generator in the laser
  - Best atmospheric transmission and more larger atmospheric turbulence structure
  - Less solar noise

Expected gain in IR compared to green link

Elevation angle	**20°**		**40°**	
Retro-reflectors	A11/A14/A15	L1/L2	A11/A14/A15	L1/L2
GAIN IR/Green				
Laser	3			
Divergence	1.3			
Atmospheric transmission	$(1.9)^2$		$(1.32)^2$	
Retro-reflector central intensity & velocity aberration	1.28	2.14	1.28	2.14
Total	**17**	**28**	**8**	**14**

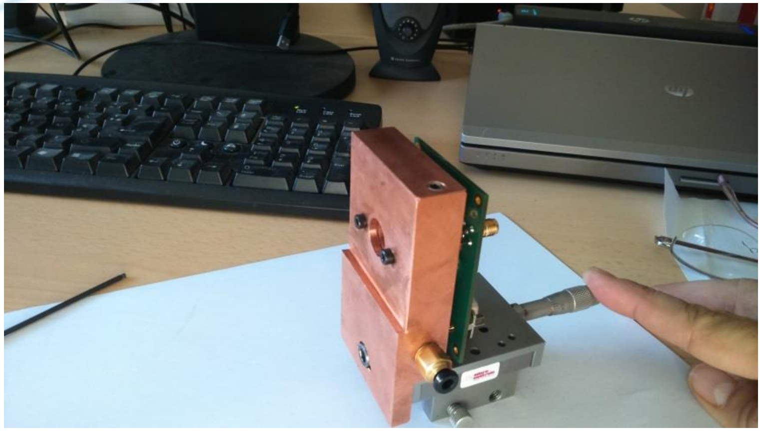
IR SPAD for LLR

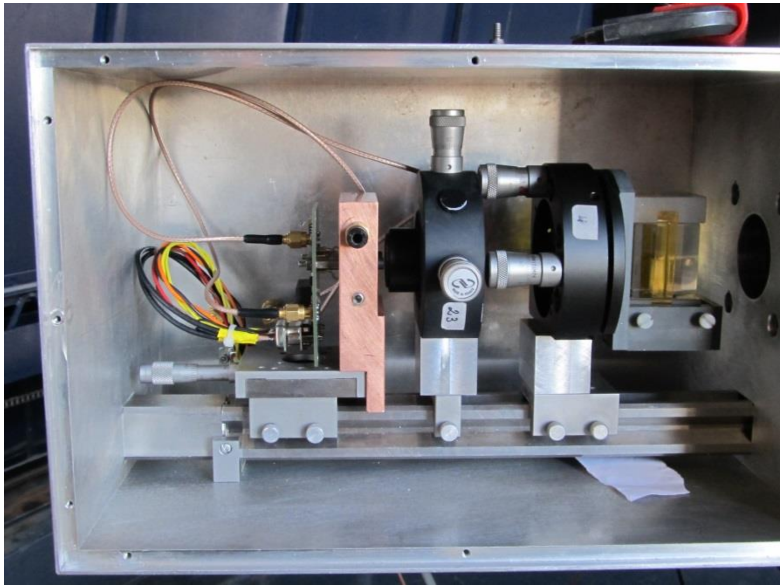
- First works on IR detector
  - On silicium detector: Samain & Mangin 1994; Schreiber et al. 1994), but at that time, the precision level of IR detection was clearly insufficient. They had also a high level of internal noise. Measurements were limited by the detector timing jitter.
  - IR detectors based on InGaAs or Ge technologies, were very noisy compared to green ones, requiring complicated cooling systems (Cova et al. 1994; Prochazka et al. 1996).

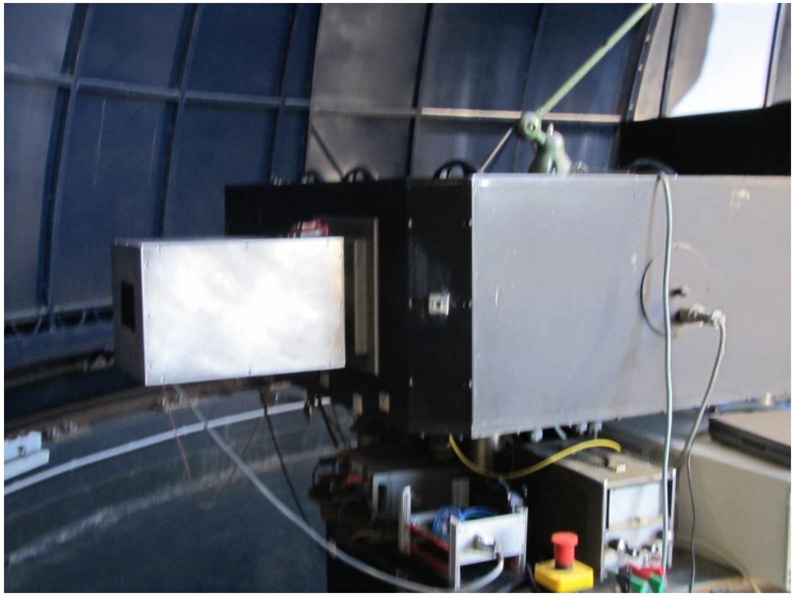
IR SPAD for LLR

- Princeton ligthwave PGA-284 in TO-8 header.
  - Quantum efficiency 20% in Geiger mode
  - DCR < 30 kHz @ +10V over the breakdown @ -40°C
  - 80 µm active area
  - Timing jitter with pulse widths of 20 ps:
    - 46,2 ps rms (109 ps FWHM) with a trigger at -100 mV on the event timer (Dassault)
    - 28 ps rms (66ps FWHM) with a trig at -10 mV on the event-timer (STX)
  - Time walk of 100 ps/decade
  - Station calibration precision of 101 ps rms (compared to the 74 ps rms in green)
  - Special asks
    - TO-8 => three stage peltier for cooling

IR SPAD for LLR







Comparison of the different lunar retro-reflectors in IR

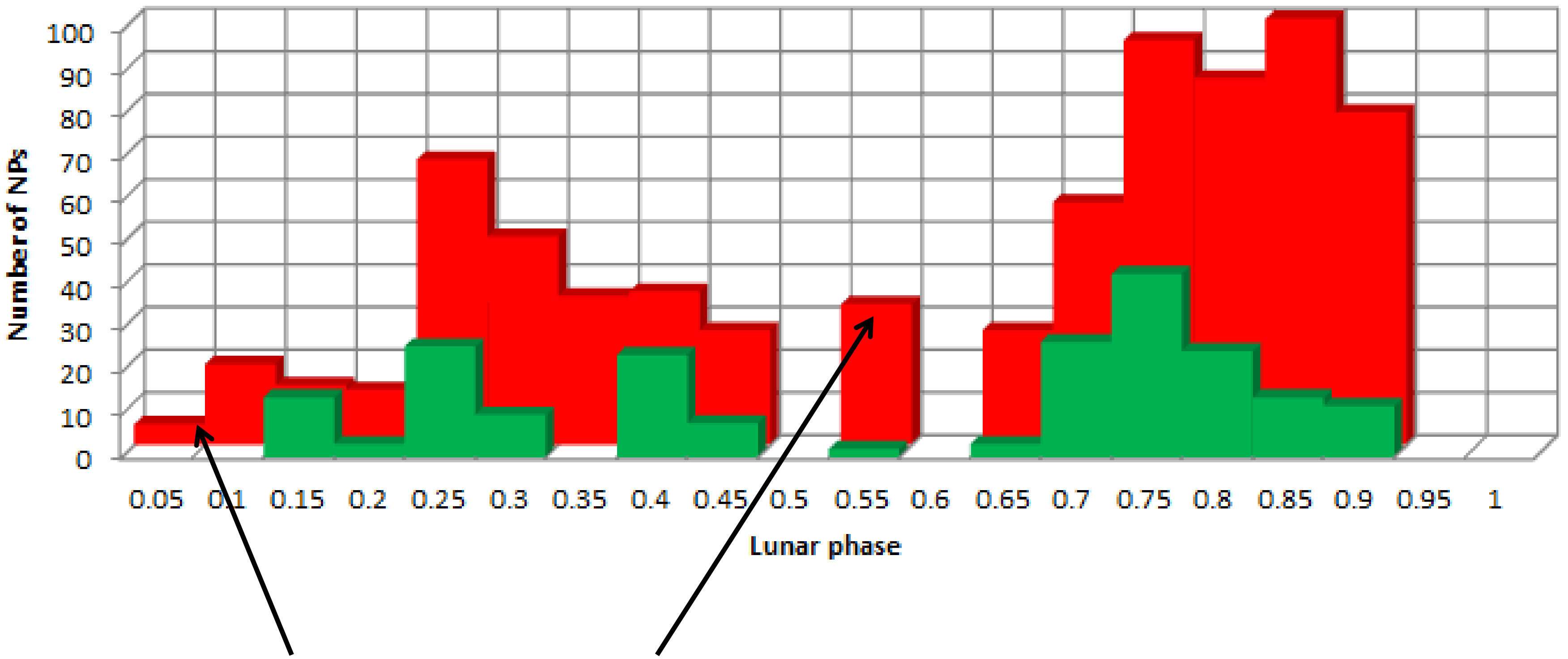
Photon flux ratio over the different lunar reflectors in IR	
Theoretical estimation	**MeO measurements**
Lunokhod arrays = **3** x A11 & A14 arrays	L2 array = **3.1** x A11
Lunokhod arrays = **1** x A15 array	L2 array = **1** x A15 array
	L1 array = **1** x A15 array
A15 array = **3** x A11 & A14 arrays	A15 array = **3.1** x A11 array
	A15 array = **3.1** x A14 array

Good agreement in IR between theoretical estimation and measurements

Photon flux ratio over the different lunar reflectors in Green	
Theoretical estimation	**APOLLO & MeO measurements**
Lunokhod arrays = **1.8** x A11 & A14 arrays	L1 array = **1** x A11 & A14 arrays
Lunokhod arrays = **0.6** x A15 array	L1 array = **0.3** x A15 array
	L2 array = **0.06** x A15 array
L1 array = **1** x L2 array	L1 array = **6** x L2 array

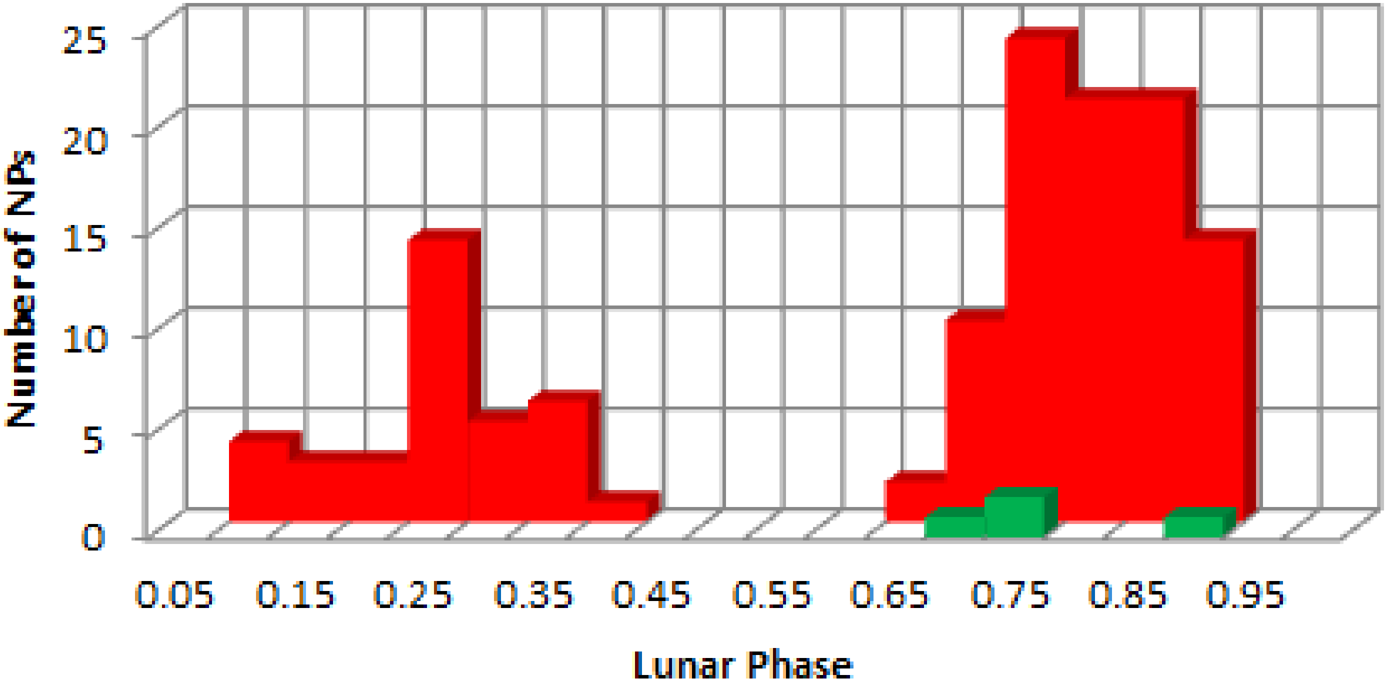
Problem in green !!!

Statistical results over the first 9 months of 2015



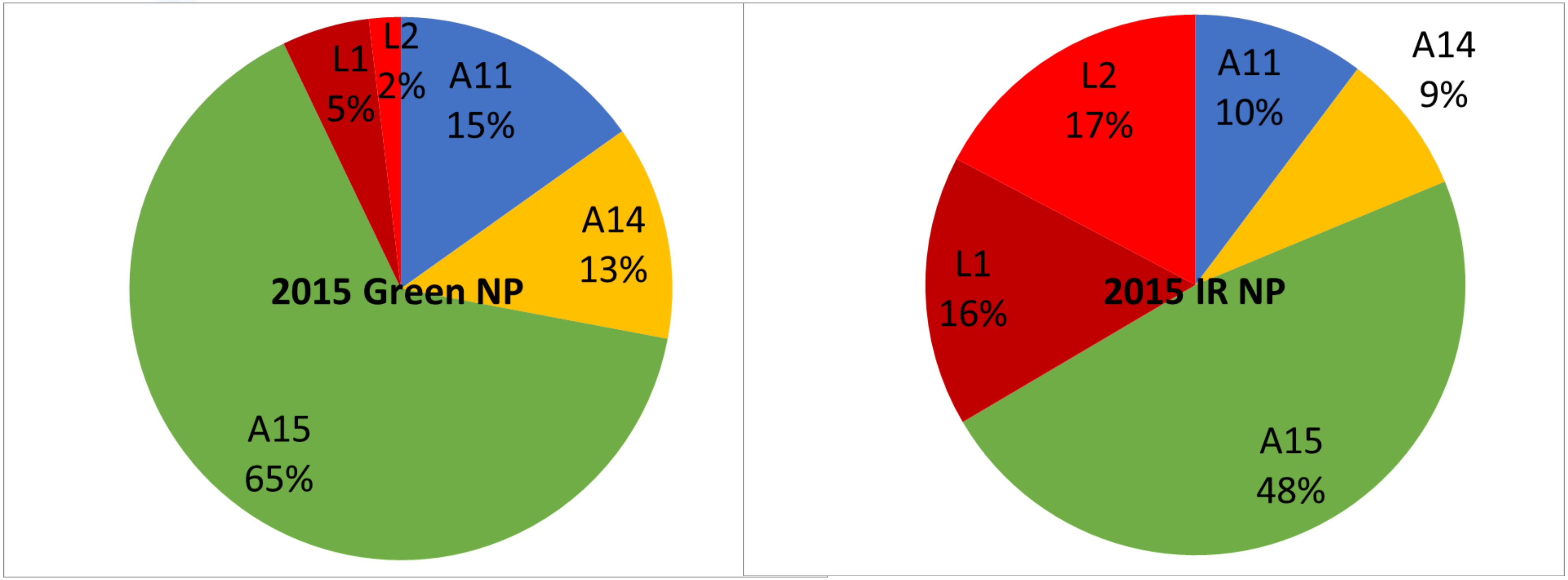
With IR, we start to fill the hole at new and full moon.
We can now observe during the day.

Statistical results over the first 9 months of 2015



L2 performs very well in IR

Statistical results over the first 9 months of 2015



Thanks to IR, LLR observations are more homogeneous over all the retro-reflectors

Statistical results

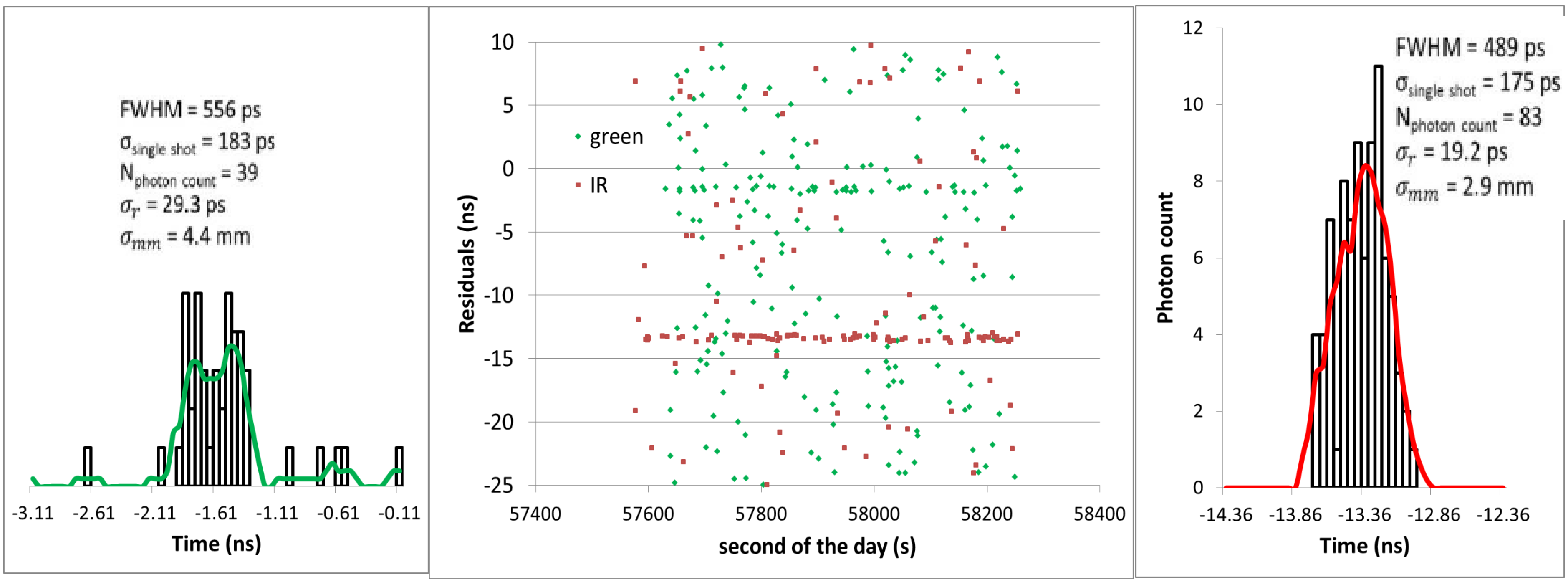
Number of different retro-reflectors followed during the night	Green LLR 2014 night number	IR LLR 2015 night number
5	1	**20**
4	11	8
3	14	18

Thanks to IR, we have more nights with acquisition on the 5 retro-reflectors

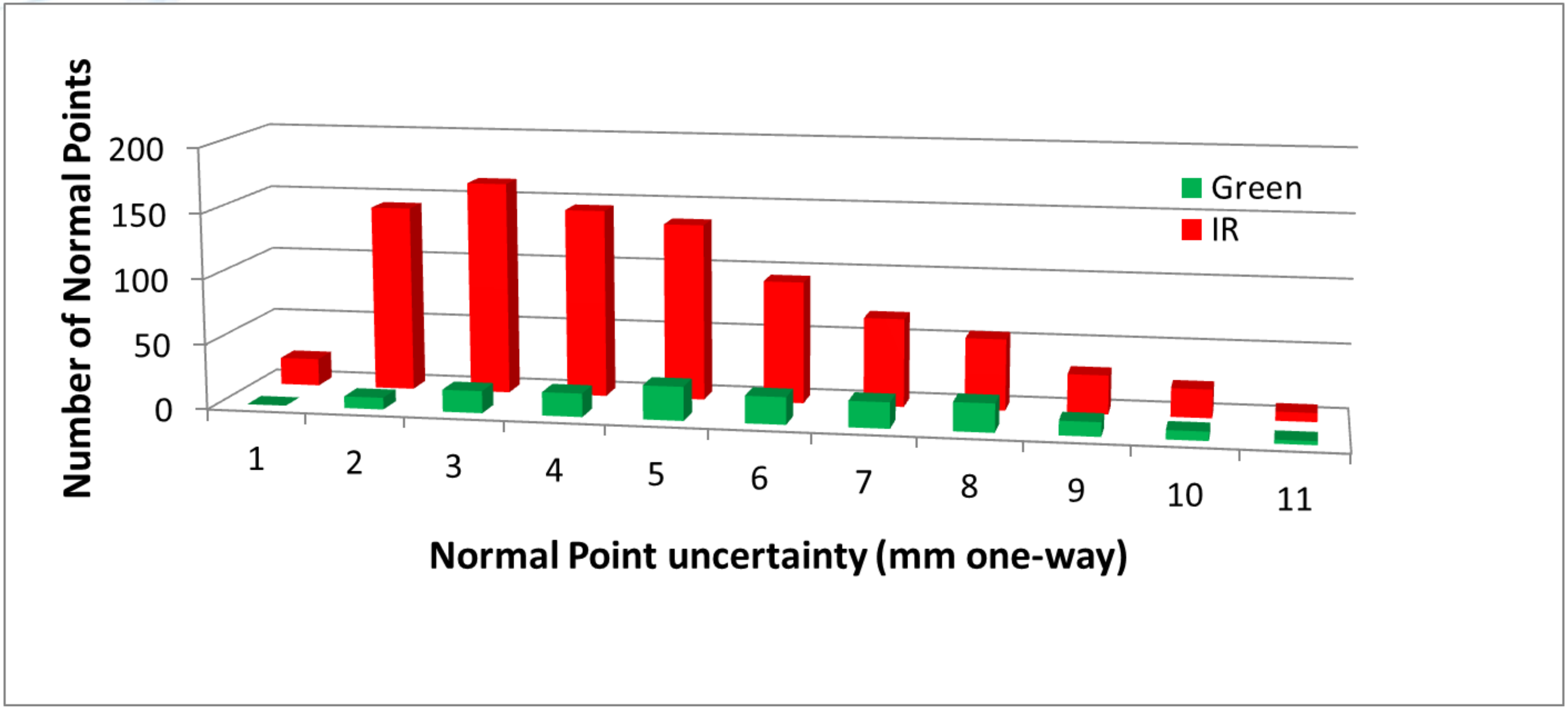
NPs precision and statistical centroid uncertainty

Statistical centroid uncertainty

$$\sigma_r = \left(\frac{\sigma_{single\ shot\ precision}}{\sqrt{N_{count}}}\right)$$



NPs precision and statistical centroid uncertainty



With IR, the NPs uncertainty is pushed between 3-4 mm, thanks to more numerous observations on L1 & L2 .

NPs precision and statistical centroid uncertainty

	11/03/2015 – 17/05/2016								
	Number of NPs								
	green	IR							
A11	27	135							
A14	19	97							
A15	137	575							
L1	9	172							
L2	1	188							

The number of NPs increases by:
=> a factor 4-5 for the Apollo retro-retroflectors
=> a factor 20 for L1 & a factor 188 on L2

NPs precision and statistical centroid uncertainty

	11/03/2015 – 17/05/2016								
	Number of NPs		Median of count number per NP						
	green	IR	green	IR					
A11	27	135	25	40					
A14	19	97	25	40					
A15	137	575	33	53					
L1	9	172	15	43					
L2	1	188	6	60					

the count number per NP increases by :
=> 1.6 for Apollo retro-relfectors
=> 3 for L1
=> 10 for L2

NPs precision and statistical centroid uncertainty

	11/03/2015 – 17/05/2016								
	Number of NPs		Median of count number per NP		Median of NP sigma (ps)				
	green	IR	green	IR	green	IR			
A11	27	135	25	40	156	163			
A14	19	97	25	40	163	178			
A15	137	575	33	53	255	271			
L1	9	172	15	43	100	142			
L2	1	188	6	60	165	153			

NP sigma are always better in green than in IR, but not for L2

NPs precision and statistical centroid uncertainty

	11/03/2015 – 17/05/2016								
	Number of NPs		Median of count number per NP		Median of NP sigma (ps)		Median of NP one-way range uncertainty (mm)		Median of NP one-way range uncertainty at the APOLLO station (Murphy et al. 2012)
	green	IR	green	IR	green	IR	green	IR	green
A11	27	135	25	40	156	163	5.2	3.9	2.4
A14	19	97	25	40	163	178	4.7	3.9	2.4
A15	137	575	33	53	255	271	6.6	5.6	1.8
L1	9	172	15	43	100	142	3.4	3.2	2.7
L2	1	188	6	60	165	153	10.1	2.9	3.3

IR improves the NP one-way range uncertainty.
We are at the same level than the APOLLO station for L2

NPs precision and statistical centroid uncertainty

Date	Array	Number of IR counts	NP sigma (ps)	NP one-way range uncertainty (mm)
2015-09-07	L2	475	129	0.9
2015-12-04	L1	297	114	1
2016-01-15	L1	278	94	0.8
2016-03-14	L1	474	114	0.8

Thanks to IR on Lunokhod retro-retroflectors, we have now NPs with one-way range uncertainty below 1 mm

Conclusion

IR detection for LLR:

- More data
- More consistent measurements
- Similar NPs precision than in green but better NPs statistical uncertainty
- No problem of reflectivity of L2 in IR

Scientific impact

- Data close to the new and full moon periods are very important for Relativity
- More nights with measurements on the 5 Lunar retro-reflectors help to constrain Lunar libration
- More measurements on L1 & L2 improve LLR quality with their smaller NP sigma

Main advantage with IR

Observers less stressed than in Yaragadee !!

Thanks for your attention