Technology Update: the 3rd generation Modulated 3D Technology

Dr. Coline Bretz, Dr. Andrea Vaccaro

The Modulated 3D technology, invented and patented by LS Instruments, constitutes a significant improvement of the 3D Cross-Correlation light scattering scheme. It increases the signal-to-noise ratio (S/N), therefore reducing the measurement duration while allowing the user to access substantially higher particle concentrations with more precision, keeping a full accuracy on the results.

After recent developments, we are now proud to introduce our latest development: the 3rd generation Modulation technology, recently patented under European Patent EP3293561. In this technology update, we summarize the background, the principle, and the benefits of this development.

Modulated 3D Dynamic Light Scattering

Dynamic (DLS) and Static (SLS) Light Scattering are powerful characterization methods providing a fast and in-situ approach to particle characterization and requiring little if no sample preparation compared to microscopy techniques. However, DLS and SLS rely on the measurement of singly scattered photons only. This means that probing concentrated suspensions by standard DLS and SLS, i.e. without any methods to filter out multiple scattering arising in those conditions, will result in significant undetectable errors in the results. Suspensions thus must be diluted, often substantially, to obtain accurate results. However, dilution is a time-consuming step that often modifies the properties of the system. Furthermore, limited available sample volumes and the need to re-use the native sample in additional analytical techniques frequently prevent dilution at all.

In the early 1990s, the 3D Cross-Correlation technique was mentioned for the first time in the works of K. Schätzel [1]. 10 years later, it was embedded for the first time in a commercial instrument, the 3D LS Spectrometer.

In this measurement scheme, multiple scattering is suppressed from the signal, yielding accurate results independently of the concentration considered. This is achieved by performing two simultaneous light scattering experiments, and then performing a cross-correlation of the resulting signals to identify the common single scattering information in both detection channels [2]. Additionally, DLS and SLS users can directly view if multiple scattering is present, as part of the signal will be missing. In the 3D LS Spectrometer, this is displayed in the software as a reduction of the correlation function intercept β. β is a direct measure of S/N and takes a value close to 0.25 in 3D cross-correlation measurements due to crosstalk between the detectors. In standard DLS, β is closer to the ideal value of 1.

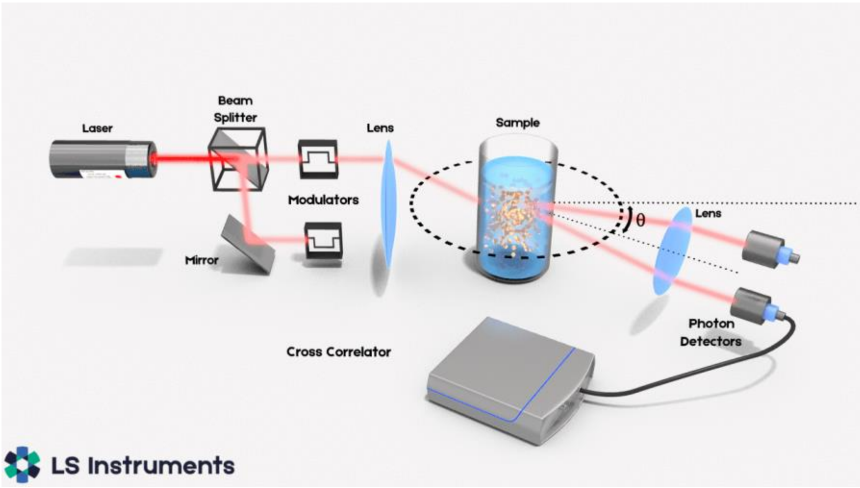
---

[1] K. Schätzel, Suppression of Multiple Scattering by Photon Cross-correlation Techniques, J. Mod. Opt. 38, 1849 (1991).

[2] For more information, please visit https://lsinstruments.ch/en/theory/dynamic-light-scattering-dls/3d-cross-correlation

While the 3D Cross-Correlation is a powerful technique that provides accurate results at any concentration, the reduced β constitutes a notable drawback for the user. This is because multiple scattering arising in highly concentrated samples, despite being suppressed by 3D Cross-Correlation, contributes to a lowering of the S/N and therefore requires extended time to ensure a similar precision as obtained with standard DLS: the higher the turbidity, the lower the S/N becomes, and consequently the longer the measurement takes – despite achieving 100% accuracy.

The Modulated 3D technology[3] has been developed and patented to address exactly this limitation. By temporally separating the two light scattering experiments conducted using acousto-optic modulators (AOMs), crosstalk between detectors is removed and the S/N is increased by a factor of 4 back to the value typical of standard DLS. This technology effectively reduces the measurement time required and increases the highest concentration measurable. We provide in Figure 1 an illustration of this technology.[4]



In the first implementation in 2010, the modulation period, i.e. the time interval each light scattering experiment remains active, was restricted to 3200 ns. As this time corresponds to the fastest achievable lag time, optimal use of the Modulated 3D technology was restricted to the sizing of particles above 50 nm in radius.

In 2016, the performance of the Modulated 3D technology was improved by a redesign of the hardware, and the 2nd generation Modulated 3D was launched together with a new product: the LSI Correlator. This improvement resulted in reduced modulation times down to 800 nanoseconds, and consequent access to lower lag times, and a drastic reduction of detected light losses. Nevertheless, accessing lower lag times and consequently, lower particle sizes remained a challenge. A lowest achievable lag time of 800 ns for a measurement at 90° on an aqueous suspension allows the sizing of particles of radius above 12 nm. For nanosystems with radii below this size, it remained necessary to use the 3D Cross-Correlation geometry. In such cases, optical path length reduction methods[5] and/or increased measurement time were used to ensure both result accuracy and precision.

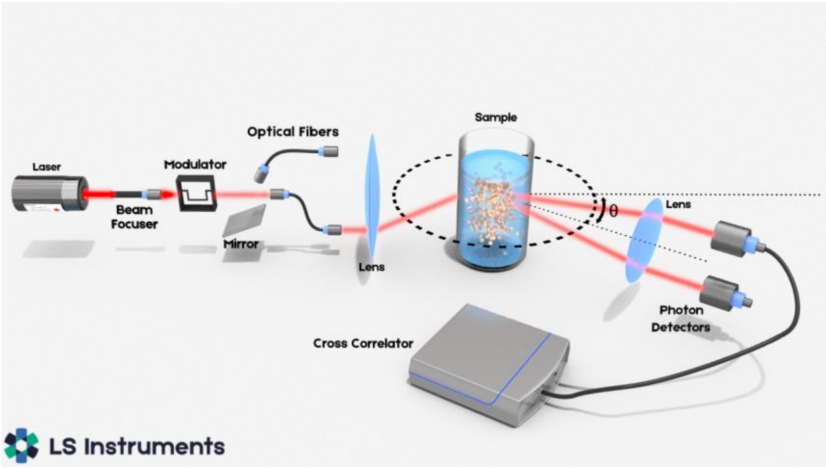
---

[3] I.B. Block, F. Scheffold, Modulated 3D cross-correlation light scattering: Improving turbid sample characterization, Rev. Sci. Instrum. 81, 113103 (2010).
[4] An animated illustration can be found on our website
[5] For more information please visit (webpage on corner measurements to be made from my notes)

The 3rd generation Modulated 3D technology

Principle

The limiting factors to the modulation period, and hence the lowest attainable lag time, are the switching time of the AOMs which is dictated by the size of the laser beam: the smaller the laser beam size the faster the switching time. We solved this limitation by focusing the laser beam as it passes through the AOM, using an optical fiber coupled to a beam focuser. This scheme is illustrated in the figure below[6]:



In this implementation, the time required to switch between channels A and B is reduced by a factor of 4, and as a consequence, the faster accessible lag time is reduced by the same factor. On top of this improvement, the design was made more compact, requiring only one AOM as opposed to two AOMs in previous implementations. The use of a single AOM allowed us to use the same full power laser beam instead of splitting it in two as in the previous implementations, thus yielding a theoretical two-fold increase of the detected light intensity. Lower switching times translate into lower lag times accessible in the correlation function, and consequently in the ability to measure to lower sizes, typically 3 nm in an aqueous suspension. Higher detected light intensities, in turn, allow for substantial measurement time reductions while keeping the same S/N.

Performances

The benefits of this technology update can thus be summarized as follows:

- Access to sizes four times lower than in the previous implementation.
- Faster measurements thanks to an increased detected light signal
- Compact implementation

We illustrate the increased detected light signal and the lowered faster accessible lag time in the figure below:

---

[6] An animated illustration can be found on our website

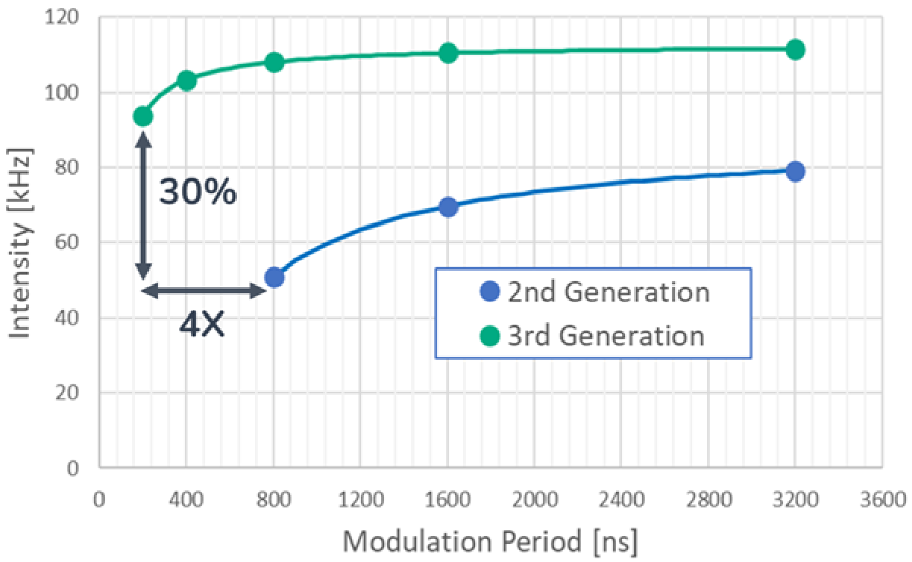


Figure 2. Measured scattered intensity as a function of the modulation period for the 2nd generation technology and the 3rd generation implementation. We observe a four-fold decrease of the faster lag time accessible and an increase of 30% In the detected light Intensity.

We can appreciate how the faster accessible lag-time decreases by a factor of four from 800 ns of the 2nd generation down to 200 ns of the 3rd generation implementation, thus allowing the same reduction of the smallest measurable particle size. We also see that at the fastest lag time the detected light intensity is increased by 30%, hence decreasing by the same amount the measurement time required to attain a given measurement precision.

In order to provide the reader with a better overview of the advantages and limitations of each DLS technology, we summarize the most important points in the table below:

	Accuracy	High S/N: measure very turbid systems	Sizing down to 12 nm	Sizing down to 3 nm	Sizing down to 0.15 nm
Standard DLS	no	no	yes	yes	no
3D Cross-Correlation	yes	no	yes	yes	yes
1st Generation Modulated 3D	yes	yes	no	no	no
2nd Generation Modulated 3D	Yes	yes	yes	no	no
3rd Generation Modulated 3D	yes	yes	yes	yes	no

From the table, we notice that despite its limitations, the 3D Cross-Correlation technology is the only DLS implementation that, being able to measure down to 12.5 ns lag times, allows to size reliably particles below 3 nm down to 0.15 nm. It is worth mentioning, as a closing remark, that in the rare case where the sample is too concentrated even for the latest Modulated 3D Cross-Correlation implementation, the user can resort to the so-called optical path length reduction. This entails placing the measurement cuvette such that the scattering volume, i.e. the crossing of the laser beam and the detection "virtual beam", is placed as close as possible to its corner. This is implemented in both the NanoLab 3D and 3D LS Spectrometer. [7]

Summary

The Modulated 3D technology constitutes a significant improvement to the fail-safe 3D Cross-Correlation scheme in light scattering. However, in previous implementations, the lowest size measurable in DLS was restricted to 30 nm due to the fastest lag time of the measured correlation function being limited to 800 ns. Following an implementation redesign that reduces the number of AOMs from 2 to 1, users can now benefit from improved accuracy, high S/N, and access to particle size down to 3 nm. Further guidance is provided to the reader for optimal measurements on lower particle sizes.

[7] For more information please visit https://lsinstruments.ch/en/products