

High Accuracy Absolute Long Distance Measurements using fs-laser metrology

Summary Report

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1 Documents & Abbreviations

1.1 Applicable Documents

	Applicable Documents	Document number	Issue
AD01	SOW in Appendix 1 to AO/1-5070/06/NL/HE	GS 05/B20	1.0
AD02	Absolute long distance measurement with (sub-) micrometer accuracy for formation flight applications (Technical Proposal)	TNO-ALDM-PROP-002	1.0
AD03	TN1 State-of-the-art Technology Review and Preliminary HAALDM Concepts	HAALDM-TN1	1.0
AD04	TN2 Technology Status Review and Refined Femtosecond-based HAALDM Concepts	HAALDM-TN2	2.0
AD05	TN3 Parametric HAALDM System Study	HAALDM-TN3	2.0
AD06	TN4 Femtosecond-based Distance Metrology Systems for XEUS and Darwin	HAALDM-TN4	2.0
AD07	TN6 "Recommended R&D Programme for Spaceborne Femtosecond-based Distance Metrology Systems: (A) General, (B) Darwin, (C) Xeus"	HAALDM-TN6	1.0
AD08	Final Report, Compilation of updated Technical Notes produced under this contract, including performance models and any produced output files.	HAALDM-Final Report	1.0

2 Introduction

This document is the summary report of the HAALDM project. (Absolute Long Distance Measurement with (sub-) micrometer Accuracy for Formation Flight Applications, ESA Contract number 20183/NL/HE)

The objective of the study is to assess the feasibility of FS-laser-based absolute long distance metrology in space and to explore its range of applications. The work comprises a parametric study for various FS-metrology schemes. These schemes represent a number of missions. Important aspects here are not only the required measurement range resolution, but also the role in the mission scenario and corresponding specifications in terms of spacecraft constellation and distance. To achieve this, the study investigates:

- Limitations of FS-metrology. This can be divided in
 - Fundamental limitations
 - Technological limitations
 - Technical realisation
 - Maturity of the involved technology
- Applicability of FS-metrology to different space mission scenarios
- Demands on system level

Where needed (where critical parameters are not documented sufficiently in literature) the study is supported by a limited experiment. In addition to the assessed performance of the FS-metrology schemes, they are compared to potential alternative measurement techniques, like frequency sweeping interferometer or dual wavelength interferometer. For the Darwin and the XEUS missions a HAALDM set-up is designed.

This Summary report gives an overview of the findings of the activities performed under this contract in a concise manner. For more detailed information the reader is referred to the Technical notes that have been written within this contract.

3 Study results

An extensive literature research has been performed to assess the state of the technology in the field of frequency combs and length measurements using these lasers. All the results have been discussed and comprehensive overviews have been added. In the paragraphs below the most important parts are discussed separately. For more detailed information on the principles of operation the reader is referred to the technical notes. [TN1 and TN2]

3.1 Frequency combs

To summarize the discussion on the various types of laser systems given in TN1 and TN2, a table has been compiled (see Table 3-1) with the main characteristics of each type of femtosecond oscillator discussed here:

fs-laser type	f_{rep} range	Phase stability	Pulse duration	Wavelength	Pulse energy	f_{ceo} stability (1 ms)	f_{ceo} stability (1 s)
Ti:Sapphire	50 MHz - 1GHz	100 mrad	6-100 fs	800 nm	10 nJ	10^{-7}	10^{-11}
Er-doped fiber	20 MHz - 100 MHz	1 rad	80-200 fs	1550 nm	1 nJ	$\sim 10^{-6}$	$\sim 10^{-10}$
Yb-doped fiber	20 MHz - 300 MHz	<1 rad	80-200 fs	1040 nm	10 nJ	$< 10^{-6}$	$< 10^{-10}$
Diode laser	1 GHz - 30 GHz	N.A.	1-10 ps	~ 1500 nm	10 pJ	N.A.	N.A.

Table 3-1 Overview of the main parameters for various types of femtosecond lasers.

In addition to the data presented in this table, the f_{rep} -stability is of course also a major parameter for HAALDM schemes. For all types of lasers, this stability has been found to be mainly limited by the reference frequency source that was used for f_{rep} -locking. Only the diode laser (for which only limited data is present) is seen to have significantly more noise, due to its active mode-locking mechanism and its higher susceptibility to high-frequency noise. This leads to about an order of magnitude worse stability compared to the other lasers.

At a later stage in the studies it has been identified that the hybrid mode-locking of a diode laser would be a good way to achieve a decent level of F_{rep} stabilization, needed for length measurements. At the Final presentation meeting the most recent data has been presented, showing that this approach is a valid design options for a HAALDM system.

Aside from this table, a list containing the main advantages and disadvantages of each type of fs-laser system for implementation in space-based HAALDM schemes is shown in the Table 3-2.

fs-laser type	Main Advantages	Main Drawbacks
Ti:Sapphire	high accuracy, good phase noise, short pulse duration, high output power	alignment sensitive, high power consumption
Er-doped fiber	high accuracy on longer timescales, all-fiber setup, easy dispersion control	significant phase noise, limited repetition rate
Yb-doped fiber	compact, high output power, high accuracy, (possibly) good phase coherence	all-fiber setups technically involved, large-ratio dispersion management needed
Diode laser	very compact, low power consumption	higher noise level, long pulse duration, weak output, only relative combs (on short term)

Table 3-2 Overview of the main advantages and drawbacks for various types of femto-second lasers.

3.2 Comb references

Two important components for a length measurement system are the frequency stabilization and referencing and the carrier envelope phase offset stabilization. In general the performance of a frequency comb (or length measurement system using a comb) often is limited by the clock that is used to stabilize it. Therefore the studies have dealt with the two types of stabilization extensively. First of all the various techniques have been discussed and secondly the availability and performance of frequency references was regarded.

3.3 Length measurements using frequency combs

Three different principles of length measurements using a frequency comb are reported in literature. These are:

- Optical heterodyning. An interferometer is build up where the path length difference between an external measurement arm and an internal reference arm is determined. The length measurements are performed in two steps. In the first step the number of pulses between the two arms are determined, giving the rough distance. In a second step the exact pulse overlapping conditions are determined by either measuring the envelope of the interacting pulses, or the resulting interference fringe phase.
- Electrical heterodyning. Here the pulse trains are converted to electrical signals, where the relative overlap determines the measure electrical phase difference between these pulse trains.
- Chromatic techniques. By dispersing the light of the two pulse trains in a cross-correlator the overlapping conditions can be imaged onto an area detector directly.

Each of these techniques has been analyzed and the critical performance parameters were identified. In the table below an overview is given of the three most important sources in literature.

Techniques	Weight	fs-Comb based Methods			other Methods	
		<i>Jun Ye</i> TOF 2 f_{rep} fs-pulse ranging & fs-Comb Cross Correlation Interferometry	<i>Minoshima & Matsumoto</i> Two harmonic fs-Comb beat signal ranging	<i>Seung-Woo Kim</i> TOF CW AM Modulation & fs-Comb Dispersive Interferometry	DWI & FSI	TOF CW FM Modulation
Long Range Capability (> 100 m)	25%	↗	↗	↘	→	↗
High Accuracy Capability (sub μ m level)	25%	↗	→	↘	→	↘
fs-Comb Requirements Complexity (f_{rep} & f_o)	15%	↘	→	→	↘	□
Sensor Measuring Rate (> 10Hz)	5%	↘	↗	→	→	→
Electronics and Processing Complexity	10%	→	→	↘	↘	↘
Sensitivity to Noise	10%	→	↘	→	↗	□
Sensor Robustness (to specs derating)	10%	→	→	↘	↘	→
TOTAL	100%	74%	69%	39%	54%	47%

Critical	□	10%
Hard	↘	30%
Regular	→	60%
Simple	↗	100%

Table 3-3 Overview of length measurements in literature and comparison the traditional alternatives.

4 HAALDM concepts

Having identified the different ways to determine the length and the possible implementations of the detection one can create an overview of all possible combinations. Each combination has its own specific performance and properties.

During the studies all these options were regarded and for each option an assessment has been made of the achievable performance for operation in space in terms of operating distance and accuracy. Here the main system parameters, such as frequency stabilization and type of laser are considered. In Figure 4-1 an overview of all the identified options is given, as well as the associated working range and accuracies.

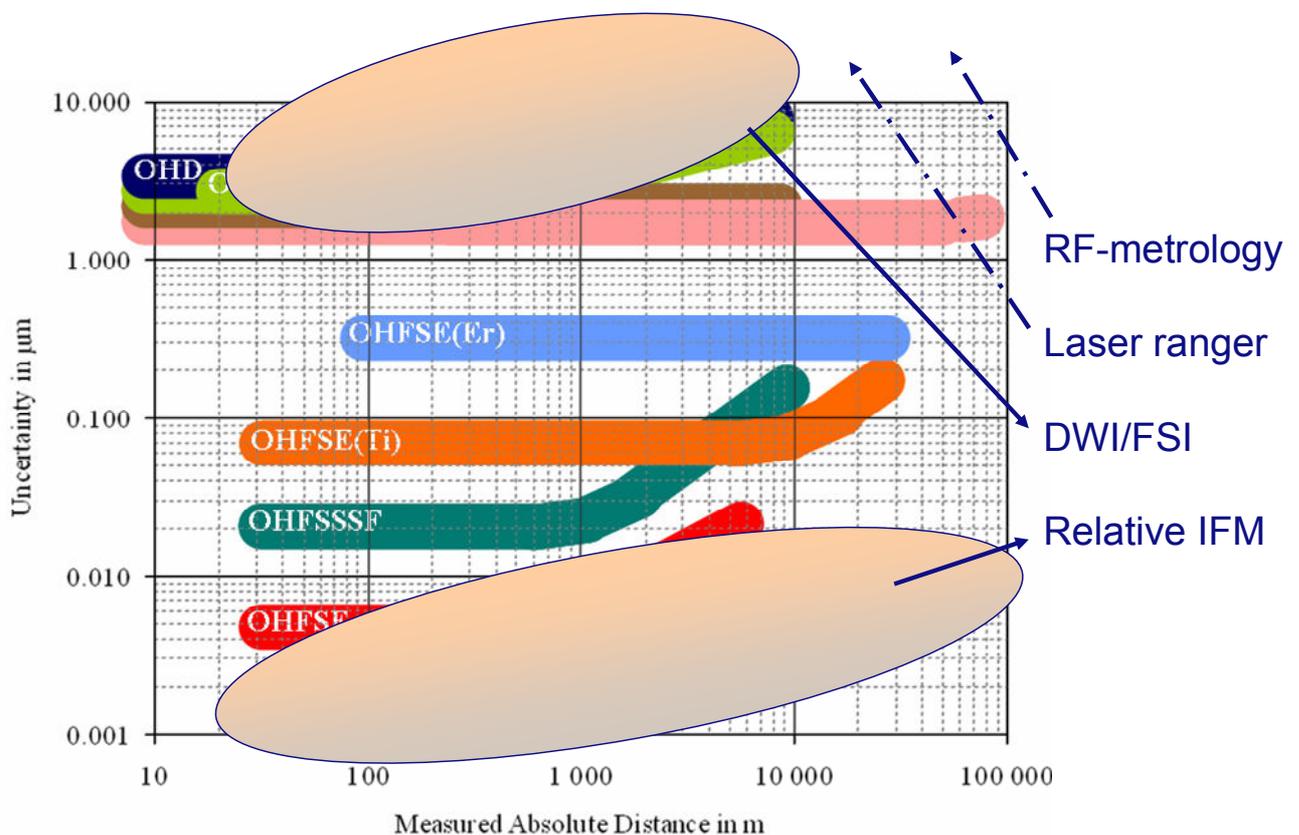


Figure 4-1 Overview of HAALDM concepts and the associated operating ranges and accuracies also in relation to traditional length metrology, such as DWI/FSI and heterodyne interferometry.

From Figure 4-1 it is clear that HAALDM is a technique that can be used for length measurements over small distance ranges as well as very large distance ranges. Distances up to tens of kilometers seem feasible. The accuracies that can be achieved typically are in the micrometer range but few nanometers can be achieved as well in the most extensive options.

Important to notice, is that the micrometer accuracies can be achieved rather easily using the most simple HAALDM-scheme, where the alternative techniques like dual wavelength interferometry already are becoming complex systems.

In addition it should be observed that HAALDM offers systems that work in the range between the traditional systems for relative and absolute distance measurements. However HAALDM offers absolute distance measurements and not just relative. In other words the overall achievable absolute distance accuracies are improved from the micrometer to the nanometer level by the introduction of HAALDM.

5 Missions and requirements

In the statement of work 4 target missions were indicated with varying range and accuracy requirements. These missions are:

- Darwin. A flotilla of 4 to 7 satellites flies in formation with accuracies of tens of micrometers to form a large base telescope. The path length stabilization is to the nanometer level.
- XEUS. Two spacecraft fly in formation with an accuracy better than 1mm, to form an X-ray telescope together. Using a micrometer accurate triangulation measurement system the detector spacecraft follows the mirror spacecraft.
- Interferometry for the measurement of the Earth's gravity. Two spacecraft follow each other in a Low Earth Orbit. By measuring the changes in the separation of proof masses in the spacecrafts, the Earth's gravity field is measured.
- LISA. Three spacecraft form an equilateral triangle with a 5million kilometer base length. Relative length changes between the arm lengths are measured to the picometer level in order to measured gravitational waves.

Most other missions that use formation flying can be compared very well to one of these four missions in terms or requirements.

During the studies the applicability of HAALDM to each of these missions was studied extensively. It has been identified what the potential gain would be of applying HAALDM to each of these missions and what the corresponding requirements would be to the HAALDM system. In Table 5-1 an overview is given of the possible HAALDM concepts and their performance in terms of the mission parameters range and accuracy.

From the analysis it was concluded that:

- Absolute distance measurements with accuracies of about 1micrometer over distances of up to few hundreds of meters for Darwin and XEUS seem feasible. The resulting requirements on the HAALDM system are very mild for frequency comb application. Therefore the most simple frequency comb application would be suggested, which would yield lower mass and power consumption than the presently proposed systems.
- Applying HAALDM to the LISA mission is un-logical since the required accuracy cannot be met.
- Applying HAALDM to the Earth gravity mission seems unlogical, because the resulting system would be more complex than the presently proposed heterodyne interferometry.
- Due to changes in the mission priorities within ESA it is hard to address a good target mission at this stage.
- HAALDM offers a large range of possibilities for absolute distance measurements that would fit missions requiring accuracies of few nanometers up to distances of kilometers.

Pulse Overlapping Procedure		Detection Scheme		Mission Parameters	Measurement range / Inter Spacecraft Separation (@ freq. stability of)			Measurement Accuracy (@ freq. stability of)			Level of meas. bandwidth	Sensitivity to spacecraft drift	fs-Laser pulse average power reqs	Main Requirements / Limitations / Critical issues	
2-fsL Phase Tuning	Trip Scan	OPD Scan	Disp. Time/Space		Intensity CC	Interferometric CC	10 ⁻¹⁰ @ ms	3x10 ⁻¹² @ms	10 ⁻¹³ @ ms	10 ⁻¹⁰ @ ms					3x10 ⁻¹² @ms
						Commercial Clock	ACES like	Optical Reference	Commerc. Clock	ACES like	Optical Reference				
					EH	from 0 m to 100 km			few µm			1 kHz	Negligible	few mW	Requires accurate phasemeter
	X				OH FSE (Er)	from several 10 m to several 100 m	from several 10 m to 10 km	from several 10 m to 100 km	several 0.1 µm			10 Hz	Small but compensable	sub mW	Requires large fsL cavity scan to achieve overlapping at tens of meter range
	X				OH FSE (Ti)	from few 10 m to several 100 m	from few 10 m to 1 km	from few 10 m to 10 km	0.1 µm			10 Hz	Small but compensable	sub mW	Requires large fsL cavity scan to achieve overlapping at meter range
X					OH 2LE	from 0 m to 10 km			few µm			10 Hz	Small but compensable	sub mW	Requires accurate phasemeter
		X			OH OSE	from 0 m to few 100 m	from 0 m to 10 km	from 0 m to few 10 km	several µm			10 Hz	Negligible	sub mW	Requires a large laser f _{rep} (>1GHz) to reduce ambiguity range
	X				OH FSF	Not stable enough	from few 10 m to few 100 m	from few 10 m to 1 km	Not stable enough	a few 10 nm	several nm	10 Hz	Considerable but compensable	sub mW	Requires f _{ceo} stabilisation
	X				OH FSSSF	Not stable enough	from few 10 m to several 100 m	from few 10 m to several km	Not stable enough	0.1 µm	several 10 nm	100 Hz	Small but compensable	sub mW	Requires f _{ceo} stabilisation
X	X		X		OH D	from 0 m to several km			several µm			10 Hz	Negligible	sub W	Requires high power levels

Table 5-1 Overview of HAALDM concepts and the related system performance

6 XEUS system design

For the XEUS mission a HAALDM system has been composed. This mission was addressed in particular because the resulting HAALDM scheme would be relatively simple and light with respect to the proposed Dual Wavelength Interferometry.

In the XEUS mission documents the position and orientation of the detector spacecraft is determined with respect to the mirror spacecraft using a set of 4 triangulation systems. In Figure 6-1 a sketch is given showing this principle.

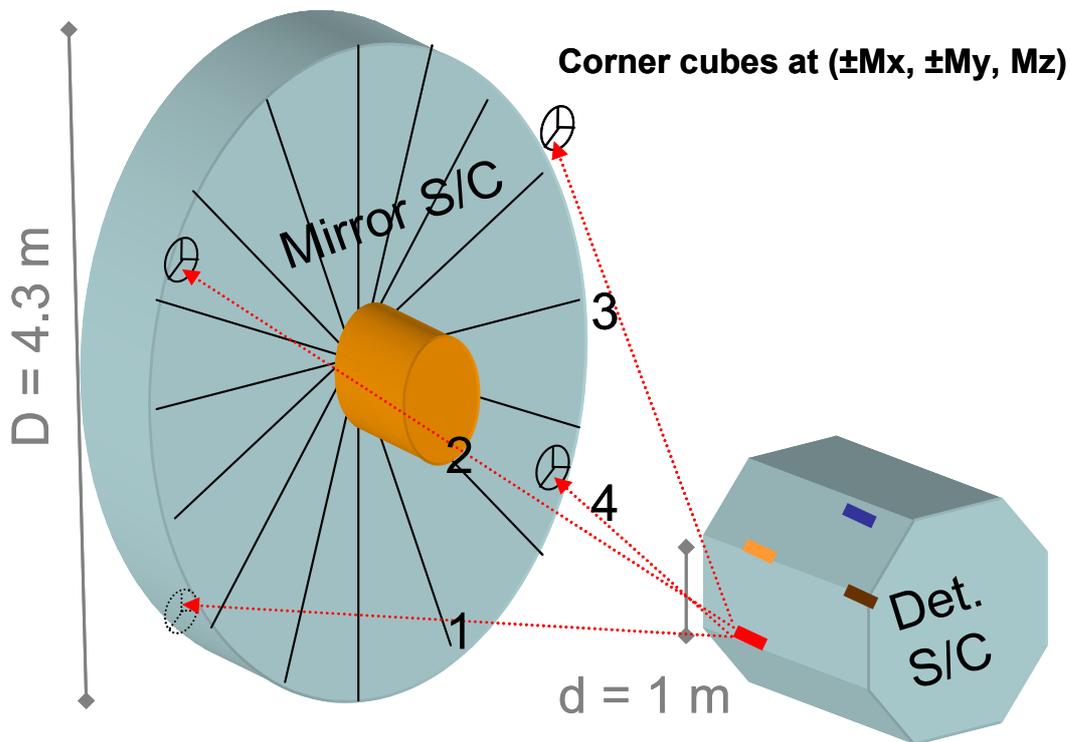


Figure 6-1 Triangulation in the XEUS mission

Within the studies a detailed design of a HAALDM system has been made that matches the XEUS requirements. The designed system composes of a hybrid mode-locked diode laser that is referenced to a simple electronic clock. The distance measurement is performed by the determining the optical pulse overlap position. To achieve the overlapping condition a delay line is scanned continuously in an oscillating mode. In the figures below the optical and electrical schemes are depicted, showing the operation of the proposed HAALDM scheme for the XEUS mission.

The resulting system design meets the range and accuracy requirements easily and it is lighter in terms of mass and power consumption than the alternative DWI metrology. In addition the requirement on the HAALDM system are very mild.

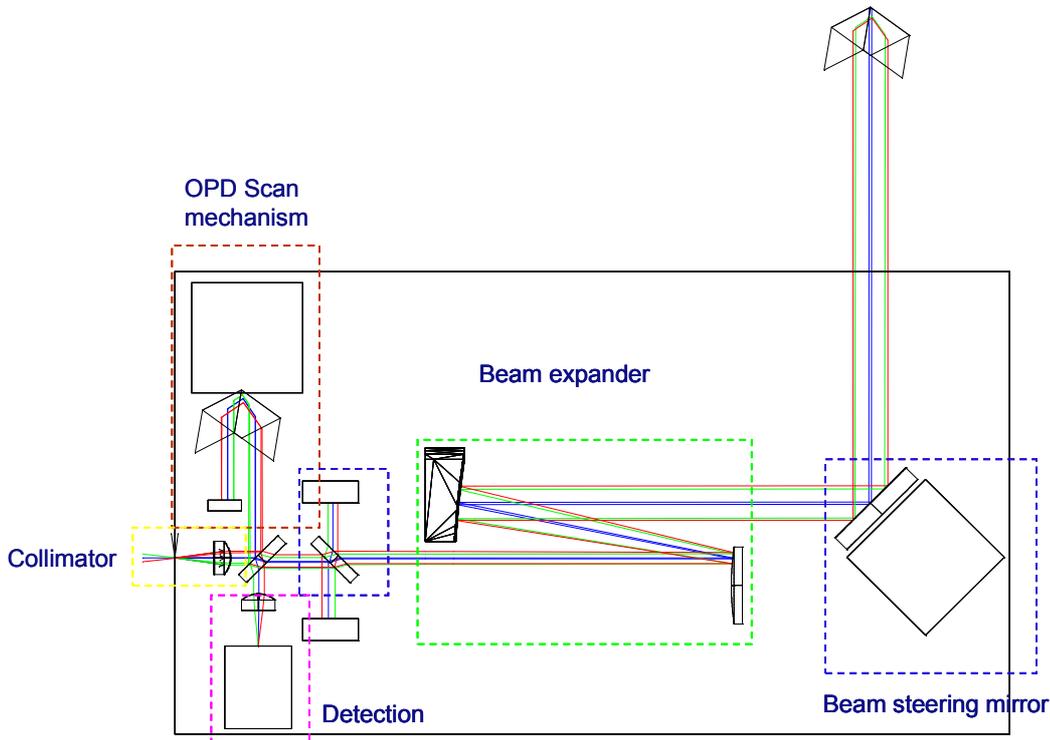


Figure 6-2 Optical lay-out of the proposed XEUS HAALDM scheme

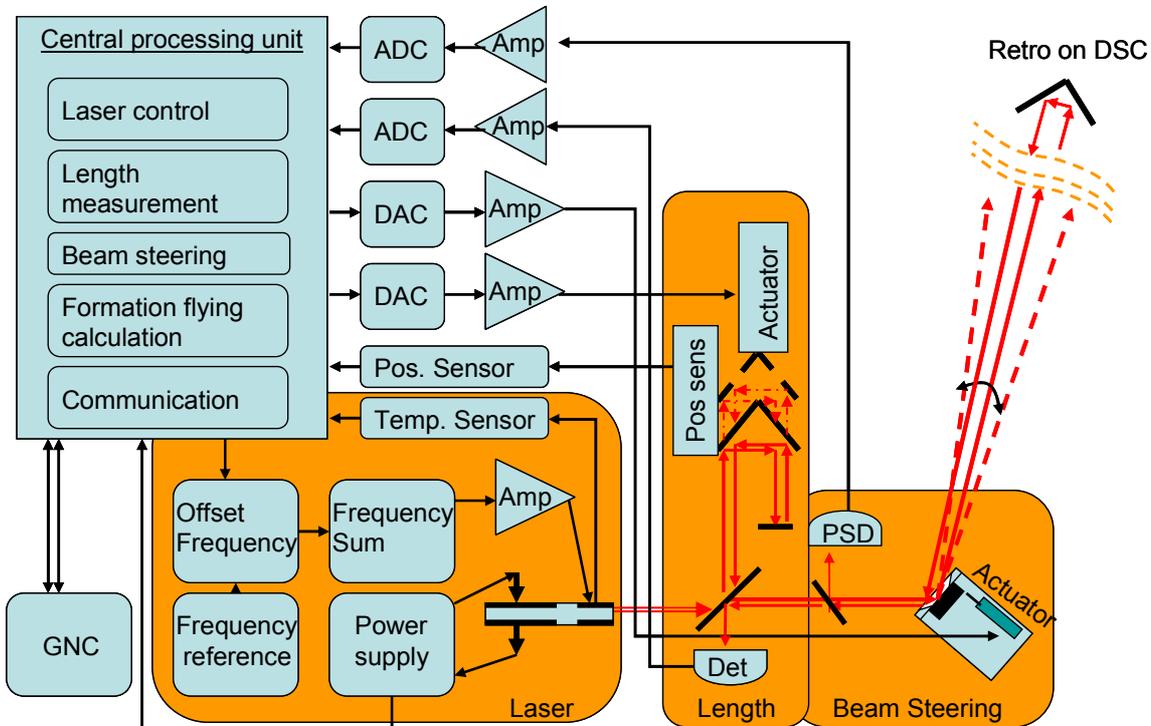


Figure 6-3 Electrical and control scheme of the proposed HAALDM scheme for the XEUS mission

7 XEUS system performance

Within the studies a large set of calculations and simulations has been performed to assess the value of the proposed HAALDM system to the XEUS mission. As a result we showed that the required accuracies can be met relatively easy, using HAALDM.

The model comprises:

- XEUS configurations with 35m nominal separation and 1m Optical Head spacing in the DSC and 4.3m diameter on the MSC
- The Trilateration method using four optical heads and four retro reflectors
- HAALDM based on femto-second lasers
- OHOSE detection scheme with also the functional parameters of its subunits
 - Laser properties such as the pulse repetition rate and pulse length
 - Frequency referencing to an external clock and the resulting frequency jitter
 - Detector and other measurement noise of both the additive type and multiplicative type
- The impact of satellite motion on the measurements

Numbers used in the calculations have been discussed between the partners in order to make them as realistic as possible. As a result the overall model is based on the expertise of the individual project partners.

An example of the result of the simulation of a typical intensity cross-correlation pattern is given in the figure below, where the horizontal axis of the top graph corresponds to the OPD of the complete ambiguity range.

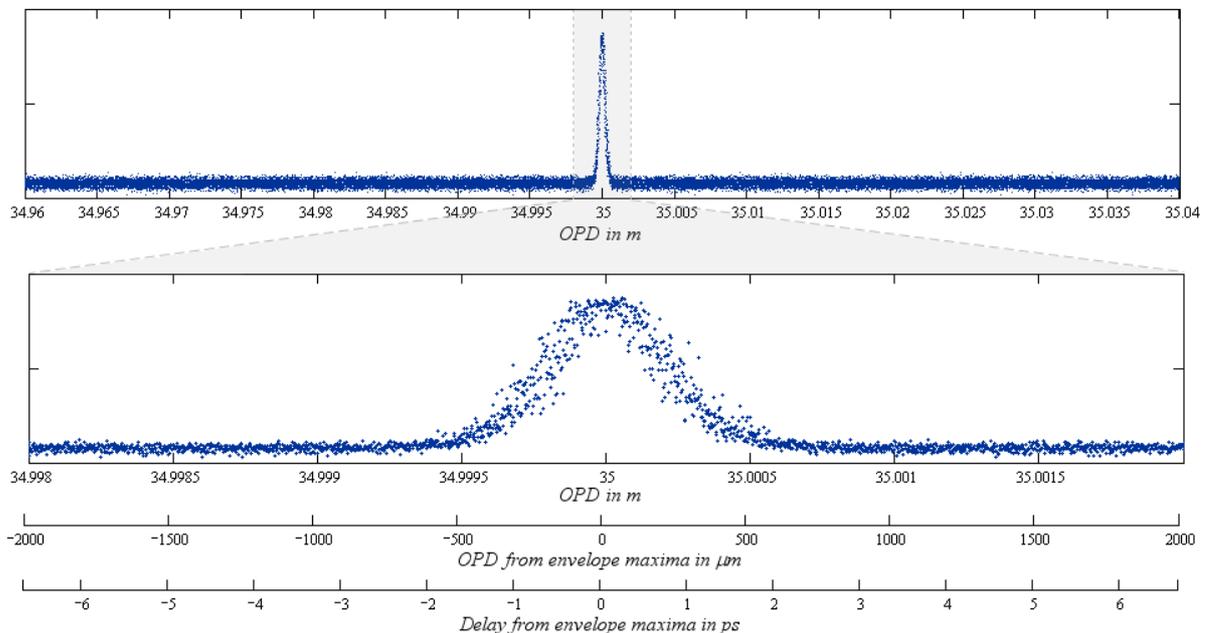


Figure 7-1 Simulation of a typical intensity cross-correlation pattern.

Figure 7-2 shows the absolute distance accuracy of the OHOSE sensor as a function of f_{rep} relative stability. In order to have an accuracy below the required $6.8 \mu\text{m}$, it is sufficient to have a stability better than 6×10^{-7} .

Comparing with the example level of stability considered in the previous stages of this study¹, this requirement is even lower than the 10^{-7} achieved with a Commercial Cs Clock.

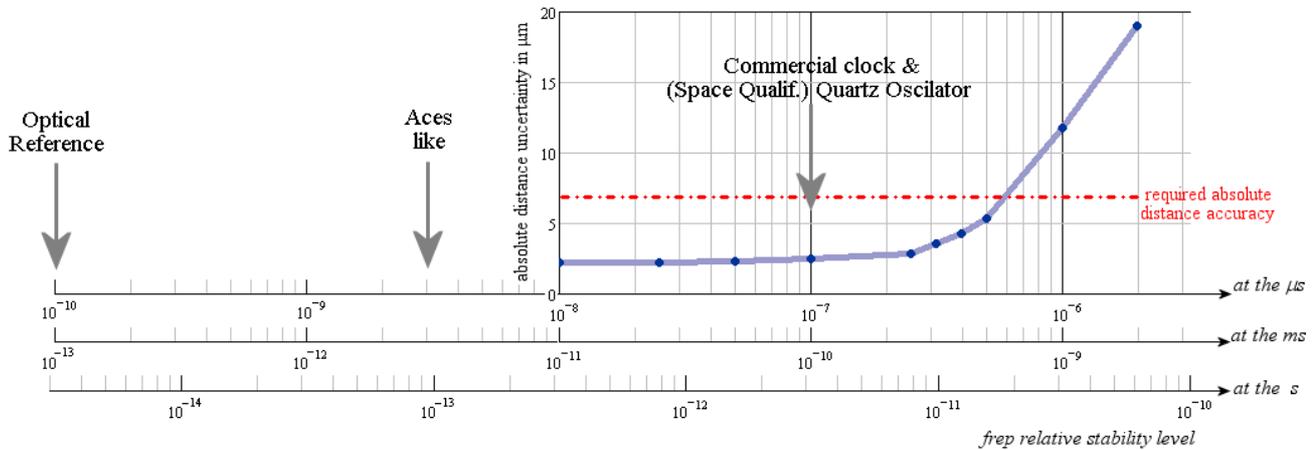


Figure 7-2 Absolute distance accuracy as a function of f_{rep} relative stability with typical clock performances indicated, for the mode-locked diode laser.

In Table 7-1 an overview is given of the XEUS mission requirements and the calculated performance of the proposed HAALDM metrology system.

Parameter	Value and range	Required measurement uncertainty (2σ)	Simulation results
z (ISD)	35 m \pm 1 m	300 μ m	10 μ m
x & y	0 m \pm 1 m	170 μ m	125 μ m
<i>pitch & yaw</i>	0 degrees	10 arcsec	1 arcsec
<i>roll</i>	0 degrees	TBD (\gg 10 arcsec)	8 arcsec
Required bandwidth	At Hz level		3Hz full cycle

Table 7-1 Comparison of required metrology performance and simulation results

¹ In the previous TN three frequency references were considered (see Figure 6.3 of TN2 [AD04]): Commercial Cs Clock, ACES like and Optical Reference with, respectively, relative stabilities of 10^{-7} , 3×10^{-9} and 10^{-10} , at the microsecond time scale.

8 Status of technology and future developments

8.1 Status of technology

During the studies an extensive overview has made of the current state-of-the-art of frequency comb metrology and the required systems and component for the realization and stabilization of such a system. It is important to notice here that the developments in this field are following each other rapidly and that therefore any overview is outdated rapidly. At the start of the studies fiber combs had repetition rates up to 100MHz, but nowadays frequencies up to 300MHz are available commercially. Recently the first two passive mode-locked laser diodes came to the market and the hybrid mode-locking mechanism was demonstrated on a diode laser.

8.2 Recommended developments

In order to arrive at the fully space qualified HAALDM system, targeted at the XEUS requirements and in the course of a few years, the following developments are recommended.

In the field of the Frequency combs, hybrid mode-locked diode lasers should be developed quickly to a commercial level, where they can be operated reliably and in a predictable way. This element is the key to efficient operation of frequency combs in space.

Clocks and references are the basis of the performance of any HAALDM system. For the proposed system a commercial clock with a frequency reference in the GHz range is required. Present space qualified crystal oscillator clocks do offer the required stability, but operate at much lower frequencies. In addition some simple electronics in the GHz range is required for detection and signal down mixing.

To prove the feasibility of the proposed metrology for the XEUS mission the building of a functional demonstrator is recommended. This demonstrator should comprise all essential and critical elements. These are:

- Hybrid mode-locked diode laser with frequency referencing
- Oscillating Delay Line with continuous operation and sub-micrometer position encoder
- Fast step and scan Beam steering mechanism with 4degrees range and returning beam position measurement

The materials used as active media in frequency combs should undergo radiation testing to asses if they can be used in space. Recently Ytterbium and Erbium fibers have been used in fiber amplifiers, already indicating that these materials could be useable. The material of interest are TiSaf, Yt- and Er-fiber and photonic crystal fibers and finally the quantum dot materials used in the laser diodes. For our proposed HAALDM-scheme the latter is the most interesting of course.

9 Conclusions from the study

The study for the assessment of the frequency comb metrology for the application of formation flying in space was conducted successfully. For this purpose a very capable team was put together with expertise from all relevant fields of subject from theoretical side to the application in the end. The project team consisted of:

- The laser Centre of the Vrije Universiteit in Amsterdam, with their leading knowledge in the field of laser, their stabilization and characterization.
- INETI in Lisbon as experts in the field of absolute distance metrology.
- TNO APPE in Delft as high-end instrument designers and manufacturers.
- EADS Astrium GmbH as experts in the field of space mission design and realization.

In terms of metrology, the FS based sensor proposed in this project, showed to be a highly valuable option for absolute distance measurements. Different sensor schemes can be envisaged, allowing for a selection of the most appropriate set of measurement ranges and accuracy, enabling the tuning of the sensor complexity according to the specific requirements.

HAALDM systems for Darwin and XEUS like missions are technically feasible. All essential components and techniques have been demonstrated in a laboratory environment and published. Here the laser source forms an exception and both a base-line and preferred design are described. The baseline design relies on a fibre laser which is available commercially from a number of suppliers, whereas the preferred design utilizes a very efficient and light hybrid mode-locked diode laser. This latter type of light source needs development before it can be used reliably.