Course Title: **Quantum Sensing & Precision Metrology**

Credit Hrs: 3

Prerequisites: Graduate-level Quantum Mechanics, Linear Algebra

Course Description:

This graduate-level course introduces the principles and techniques of quantum sensing, precision metrology, and quantum-enhanced measurements. Topics include quantum measurement theory, noise analysis, interferometry, phase estimation, entanglement, NV centers, atomic clocks, quantum imaging, and quantum radar. The course emphasizes applied concepts through simulation exercises and worked examples rather than intensive experimental setups.

Course Objectives:

- Understand quantum measurement and sensing principles.
- Analyze noise, sensitivity, and fundamental quantum limits.
- Apply interferometric and phase estimation techniques.
- Design and simulate quantum sensors using theoretical and computational tools.

Course Learning Outcomes (CLOs):

- Apply quantum measurement theory with operators, density matrices, and uncertainty principles.
- Analyze noise, sensitivity, and limits in quantum sensing applications.
- Implement interferometric and phase estimation protocols in simulations.
- Design, and simulate, quantum sensors and metrology systems.

Course Contents

Week	Contents
1	Quantum mechanics mathematical review
	Operators, Hilbert spaces, bra-ket notation, worked examples
2	Quantum noise & uncertainty
	Noise analysis, standard quantum limit, uncertainty principle examples
3	Quantum Fisher Information
	Sensitivity limits, Cramér-Rao bound, simulation of estimation

4 Spin systems & qubits

Spin-1/2, collective spin ensembles, Bloch sphere diagrams

5 Interferometry

Mach-Zehnder, Ramsey, Sagnac interferometers; simulation exercises

6 Phase estimation

Phase estimation protocols, error analysis, Python/Qiskit implementations

7 Midterm Exam

8 Entanglement in metrology

NOON, GHZ states, entanglement-enhanced sensing, conceptual diagrams

9 NV centers & atomic systems

Quantum sensor platforms, coherence times, simulation of spin dynamics

10 Atomic Clocks

Principles and technologies behind precise timekeeping. Atomic clocks based on microwave transitions, optical clocks with trapped ions and optical lattices, and key system components such as ultra-stable lasers, cavity stabilization, and frequency combs.

11 Error Sources and Analysis

Systematic error sources, environmental sensitivities, and methods for error analysis and long-term stability, applications in quantum communication, gravitational sensing, and precision navigation

12 Quantum Imaging

Quantum-enhanced imaging techniques Entangled photon generation, spatial correlations, ghost imaging, and quantum illumination applied to imaging. The module covers super-resolution methods, NOON states, interferometric imaging, and phase-super-sensitive techniques.

13 Practical considerations, such as detector efficiency, losses, and noise effects, conceptual diagrams and system-level illustrations. Simulations to demonstrate correlated-photon imaging, squeezed-light detection etc.

14 Quantum Radar

These two weeks introduce quantum radar and the principles of quantum illumination for detection in low-signal, noisy environments. The module covers entangled signal–idler photon generation, decoherence, and survival of correlations. Fundamental detection model, hypothesis testing, error probabilities, and the Helstrom bound.

15 Noise sources and correlation in Quantum Radar

Comparisons of SNR performance between classical and quantum radar are presented, along with practical considerations such as target reflectivity, thermal noise, and idler storage. SNR analysis for quantum versus classical detection, interpretation of performance metrics

16 <u>Final Exam</u>

Textbooks & References:

- Giovannetti, Lloyd, Maccone – Quantum Metrology, Phys. Rev. Lett., 2004
- Nielsen & Chuang – Quantum Computation and Quantum Information, 10th Anniversary Edition
- Mandel & Wolf – Optical Coherence and Quantum Optics, 2nd Edition
- MacDonald – Noise and Fluctuations: An Introduction

Assessment:

- Assignments: 10%
- Quizzes: 10%
- Midterm Exam: 30%
- Final Exam: 50%