

**ME 5680 Applications of Concentrating Solar Thermal Technologies**  
**Mechanical and Industrial Engineering**

4 Semester Hours

Spring, 2025

Jan 6, 2025 – Apr 25, 2025

**INSTRUCTOR:** A. Umit COSKUN

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**OFFICE HOUR:** Tue 2-3pm and Wed 1-2pm. in SN 350 (or by appointment).

**Class Meetings:**

on ground section: Mon & Wed 14:50-16:30 in Ryder Hall 285

online section (if any student is allowed and enrolled): The same schedule via video-stream in Canvas

**Course Prerequisites:** ME4570 or Graduate Standing.

There is no official prerequisite for graduate students. But graduate students are assumed to have taken a energy transfer based course equivalent of ME 4570 in their undergraduate education. For those students who did not take a heat transfer in undergraduate or graduate level, they should take a heat transfer course covering conduction, convection and radiation before enrolling.

**Course Corequisites:** None

**Course Description:** Focuses on the analysis of concentrating solar thermal technologies at the design and system levels. Discusses simulation techniques to calculate the performance of concentrating solar power (CSP) technologies, including comparisons to other solar systems in terms of efficiency and cost. Includes topics involving solar systems designs of heliostats, concentrating dishes, and troughs. Presents geometric optics and convolution techniques and integrates them with incident solar predictions to calculate the performance of CSP systems. Covers the control and tracking systems required to maximize performance; the thermal effects that occur at the high solar energy fluxes and high temperatures in CSP systems; and the potential advantages in energy generation, energy storage, and biogas manufacturing and means to predict them.

**Required Textbook(s)**

Concentrating Solar Thermal Energy: Fundamentals and Application, by Gilles Flamant, Wiley, 2022, ISBN: 9781789450798

**Important Dates:**

Jan. 19: Last day to add classes.

Jan. 20: NO CLASS (Martin Luther King, Jr. Day)

Jan. 27: Last day to drop a course without a W grade.

Feb. 17: NO CLASS (Presidents Day)

Mar. 3-9: NO CLASS (Spring Break)

Mar. 10: Midterm Exam

Apr. 21: Last day to withdraw a course (drop a course with W grade)

Apr 21: NO CLASSES (Patriots Day)

Apr 22-26: Final Exams.

## Course Topics

- Chapter 1, Solar Power Plants: State of the Art
- Chapter 2, Solar Resources Management, Assessment and Forecasting
- Chapter 3, Optics of Concentrating Systems
- Chapter 4, Solar Receivers
- Chapter 5, Heat Transfer Fluids for Solar Power plants
- Chapter 7, Materials for Concentrated Solar Power.
- Chapter 8, Thermal Energy Storage (Simulation)
- Chapter 9, Hybrid PV-CSP Systems

## Student Learning Outcomes, the students are introduced to:

- The difference between power and energy performance measures and how their differences are related to the supply and load viewpoints.
- The benefits of CSP as related to power producing or manufacturing capabilities related to the high temperatures achieved in these systems.
- Prediction methodologies for incident solar radiation at a CSP site.
- Simulation methodologies for geometric optics to determine the incident radiation on the tower receiver.
- Prediction methodologies for performance measures of the heliostat fields.
- Prediction methodologies for the thermal performance of the receiver.
- Predict methodologies for performance of thermal storage as it relates to the performance measures.

## Course Activities

1. **Activity #1:** Lecture/discussion  
Lectures to provide students with the necessary background assumed by the text and providing the necessary multidisciplinary topics.
2. **Activity #2:** Exams  
Take home midterm and final exam are given..
3. **Activity #3:** Projects  
Homework problems are designed to be small projects that are built on each other. For example, an initial homework assignment provides a system level view that requires a system definition and provides reviews of convection, thermal radiation and iterative solution techniques. This is followed by an assignment of predicting incident solar radiation in the student's home location and relating it to design requirements discussed in the introduction. These two homework assignments are then integrated with a final assignment.

## Homework Policy:

All HW assignments will be submitted electronically in Canvas as a single pdf file. Some assignments may require additional files. Supplementary files are allowed in other formats. Students can write on paper and scan and make a pdf file for their assignments. Please make sure that pages are in order, numbered, and legible in the digital scans. All due dates are set in Canvas. You will have 3 days grace period if you cannot meet the deadline of the HW assignments. You can submit in the grace period without a penalty. HW submission portal in Canvas will be closed after the grace period and no late submission allowed beyond the grace period. If you have any extraordinary circumstances (like illness) reach your instructor. We encourage discussion among classmates. However, submitted assignments should be independent work. All course-related activities are expected to be conducted according to the Northeastern University Honor Code.

### Exam Policy:

All exams will be open book and notes. You can also print out any handouts that may be posted on Canvas. You should bring a calculator to your exams.

**Take home exam policy (If any given):** The solutions must be returned at the stated due date and submitted electronically on Canvas before the deadline. NO LATE SUBMISSION for take home exams. Independent work is expected, discussion among classmates or others are not allowed. If you have questions, reach out to your instructor. All course-related activities are expected to be conducted according to the Northeastern University Honor Code.

### Grade Breakdown:

Class Participation:	15%
Homework:	25%
Exams:	25%
Final Exam and/or Project:	35%

### Grading Scale:

94-100%	A	87-89.9%	B+	77-79.9%	C+	67-69.99	D+	60% or below	F
		84-86.9%	B	74-76.9%	C	64-66.99	D		
90-93.9%	A-	80-83.9%	B-	70-73.9%	C-	60-63.99	D-		

### Weekly Schedule

This is a tentative schedule subject to change as the semester evolves.

Week 1	Introduction: what are Solar Concentrating Power Systems (CSP); History of Concentrated Solar Applications. Review: system definitions, concentration factors, combined convection and thermal radiation losses.
Week 2	Type of CSP applications, Current Developments, Emerging New Generation CSPs Current Cost Factors and Trends Introduction to Sun-Earth System.
Week 3	Prediction of Sun's position, sunrise/sunset times. Prediction of airmass, attenuation of radiation,
Week 4	Prediction of terrestrial incident solar radiation. Key Metrics for Solar Energy Measurement; Sun's angle, ISO DNI, DNI of Solar Disk, Circumsolar Radiation. Solar Radiation Measurement Techniques and difficulties.
Week 5	Solar Radiation Forecasting Techniques. Defining Concentrating Factor, Max Reachable Temperature in a Concentrating System, Assessment of Concentrating Errors. Quantification of Parabolic Trough Concentrators
Week 6	Optical Quantification of Heliostat Fields, Simulation Techniques for Heliostat Fields. Introduction to Solar Receivers and Solar Receiver Types.
Week 7	Thermal Analysis of Parabolic Trough Receivers, Analysis of Absorber Tube with a Protective Glass, Governing Equations, and Solution Strategies
Week 8	Characteristics of Parabolic Trough Receivers, Finding Temperature Distribution via Iterations. Review of Radiative Exchange via Radiosity and View Factors
Week 9	Thermal Model for Cavity Receivers, and Solution Strategies. Take home Exam 1
Week 10	Energy Flow Rates and Their Distribution in a Cavity Receiver. Influence of Cavity Design in Optical Efficiency of Cavity Receivers.

	Properties of Heat Transfer Fluids in CSP Systems. Estimation of Convective Transfer Coefficients and Pressure Drops Based on Choice of Heat Transfer Fluids. Thermal Energy Storage (Simulation) and cost factors
Week 11	Molten Salts, and Liquid Metals, and gasses as Heat Transfer Fluids, and their Impact of Convective Transfer Coefficients. Introduction to Optical Metrics within the Relevant Spectral Range.
Week 12	Achieving Desired Optical Functions; Transparent layers, Absorptive Layers, Anti-Reflective Coatings, Selective Coatings.
Week 13	Introduction to Thermal Energy Storage Systems. Molten Salt Storage Systems. Thermocline Systems, Steam Accumulators, Storage Systems based on Phase Change Materials.
Week 14	Hybrid PV-CSP systems. Review of Photovoltaic Effect. High Temperature PV-CSP receivers. Strategies Based on Spectral Splitting. Emerging PV-CSP hybrid strategies.
Week 15	Final Project.

### **Attendance Policy**

I expect students to attend the class session in order to participate and have full advantage of the discussions during them.

### **RECORDING OF CLASSES:**

All students in the on-ground section of a class are expected to attend classes in person and on time. Some courses have also online sections for remote students, which may have lecture recordings. Please note that not all programs permit on-ground students to enroll in online sections of the same course. Please note that if the circumstances require, we may record parts of lectures for educational purposes. These recordings, if any, will be made available only to students enrolled in the course, instructor of record, and any teaching assistants assigned to the course. Please also note that due to privacy laws, audio and/or video recording of any course is subject to approval. Individuals cannot perform audio and/or video recording at will. Only students who have arranged accommodation with the Disability Resource Center may use mechanical or electronic transcribing, recording, or communication devices in the classroom. Students with disabilities who believe they may need such an accommodation may contact the Disabilities Resource Center (<http://www.northeastern.edu/drc/>). Please contact me if you have any concerns.

## UNIVERSITY POLICIES and RESOURCES

### ATTENDANCE:

Attendance is an important element for success in class. If you are an asynchronous online student, viewing video streams of the lectures in a timely manner counts as attendance. Regular attendance is required unless you are unable to make it due to illness or other urgent or emergent reasons. Contact your instructor via email before the class time for allowed absence, unless you are unable to. Here is the section from the student handbook: Students will not be penalized for excused absences, with the understanding that students may need to make up for the academic commitment from which they were excused. Reasons for an excused absence include religious, medical issues, jury duty, bereavement, and military service. See the [course catalog](#) and other [applicable policies](#) for the full attendance and excusal policy.

### ACADEMIC INTEGRITY

A commitment to the principles of academic integrity is essential to the mission of Northeastern University. The promotion of independent and original scholarship ensures that students derive the most from their educational experience and their pursuit of knowledge. Academic dishonesty violates the most fundamental values of an intellectual community and undermines the achievements of the entire University.

As members of the academic community, students must become familiar with their rights and responsibilities. In each course, they are responsible for knowing the requirements and restrictions regarding research and writing, examinations of whatever kind, collaborative work, the use of study aids, the appropriateness of assistance, and other issues. Students are responsible for learning the conventions of documentation and acknowledgment of sources in their fields. Northeastern University expects students to complete all examinations, tests, papers, creative projects, and assignments of any kind according to the highest ethical standards, as set forth either explicitly or implicitly in this Code or by the direction of instructors.

Go to <http://www.northeastern.edu/osccr/academic-integrity-policy/> to access the full academic integrity policy.

### STUDENT ACCOMMODATIONS

Northeastern University and the Disability Resource Center (DRC) are committed to providing disability services that enable students who qualify under Section 504 of the REHABILITATION ACT and THE AMERICANS WITH DISABILITIES ACT AMENDMENTS ACT (ADAAA) to participate fully in the activities of the university. To receive accommodations through the DRC, students must provide the Disability Resource Center (DRC) with appropriate documentation that demonstrates a current substantially limiting disability.

For more information, visit <http://www.northeastern.edu/drc/getting-started-with-the-drc/>.

### DIVERSITY AND INCLUSION

Northeastern University is committed to equal opportunity, affirmative action, diversity and social justice while building a climate of inclusion on and beyond campus. In the classroom, members of the University community work to cultivate an inclusive environment that denounces discrimination through innovation, collaboration and an awareness of global perspectives on social justice. It is my intention that students from all backgrounds and perspectives will be well served by this course, and that the diversity that students bring to this class will be viewed as an asset. I welcome individuals of all ages, backgrounds, beliefs, ethnicities, genders, gender identities, gender expressions, national origins, religious affiliations, sexual orientations, socioeconomic background, family education level, ability – and other visible and nonvisible differences. All members of this class are expected to

contribute to a respectful, welcoming and inclusive environment for every other member of the class. Your suggestions are encouraged and appreciated.

Please visit <http://www.northeastern.edu/oidi/> for complete information on Diversity and Inclusion

## **TITLE IX**

Title IX of the Education Amendments of 1972 protects individuals from sex or gender-based discrimination, including discrimination based on gender-identity, in educational programs and activities that receive federal financial assistance. Northeastern's Title IX Policy prohibits Prohibited Offenses, which are defined as sexual harassment, sexual assault, relationship or domestic violence, and stalking. The Title IX Policy applies to the entire community, including male, female, transgender students, faculty and staff. In case of an emergency, please call 911.

Please visit [www.northeastern.edu/titleix](http://www.northeastern.edu/titleix) for a complete list of reporting options and resources both on-and off-campus

**ME 5680 Applications of Concentrating Solar Thermal Technologies**  
**Spring 2025 Semester**  
**Homework Assignment #1**

Please submit your assignment electronically in Canvas. Please make a single pdf file. If you prefer to write on a paper. You can scan and submit your HW after converting your scan to a pdf file.

Read the first chapter of the textbook, list the efficiencies of

- A solar photovoltaic collector
- solar thermal flat plat collector
- Fresnel lens solar collector
- a parabolic through solar collector
- heliostats for tower solar collector

Report a summary of your results in a tabular form.

If you prefer, you can also review recent scientific articles, technical papers or specs of recent commercial products and make comparisons between what is stated in the textbook and recent available information for these different collector types.

NOTE: we will learn more about these collector types later in the semester.

**ME 5680 Applications of Concentrating Solar Thermal Technologies**  
**Spring 2025 Semester**  
**Homework Assignment #2**

**Q1)** Read Chapter 2.0 to 2.2. (pages 45-70) and the reference for the “SPA” algorithm Reda, I. and Andreas, A. (2004) reference for the “SPA” algorithm (see pg. 48 of the textbook). NOTE: There is also a correction for this article in the same journal vol (81, year 2007, page 838)

Summarize your thoughts concerning the comparisons of the different incident solar radiations in section 2.1.1 in terms of the solar/zenith angle and solar/azimuth angle and why these parameters are emphasized instead of the incident solar radiation flux. This is more a thought-based question since will learn more about this when we cover Chapter 3.

**Q2)** You have been given the following single point design conditions; direct incident solar radiation on the collector is  $550 \text{ W/m}^2$  and the surrounding temperature is  $18^\circ\text{C}$ . You will need to estimate the power output and efficiency of the concentrating solar power (CSP) system. Perform your analysis for steady state operating conditions (although in practice this will be hard beyond short time frames) considering the following information.

The CSP will heat the working fluid from a temperature of  $32^\circ\text{C}$  and has a concentration factor of 1000 (possible with a parabolic collector). The concentration factor is the ratio of the incident solar radiation on the collector to the incident solar radiation area where it is absorbed. The optical efficiency of the collector system is 80%. The concentrating collector has an area of  $20 \text{ m}^2$ . Note that defining your system at the incident area will avoid needing the geometric optics information associated with the concentration factor. The heat transfer area of the receiver subject to outside heat loss is  $0.05 \text{ m}^2$  and assume receiver surface temperature is uniform (less likely). The absorptivity of the receiver is 0.98, and its emissivity is 0.2 (requires availability of a good selective surface, which will be covered towards end of the semester). The mass flow rate of the working fluid through the system is  $9 \text{ g/s}$ . The convective heat transfer coefficient is  $5 \text{ W/m}^2 \text{ K}$  from the receiver. For the heat transfer calculations, you can simplify the calculations considering heat interaction taking place at the average temperature of the working fluid,  $(T_{\text{in}} + T_{\text{out}})/2$ . For this problem, linearize the thermal radiation heat loss with at least one iteration. The specific heat of the incompressible working fluid is  $2678 \text{ J/(kg K)}$ . The useful energy from this collector system is the change in the enthalpy of the working fluid passing through the receiver. Once heated through the receiver, the

working fluid enters a heat engine with a thermal efficiency of 30% that is connected to a generator with an efficiency of 90%. The generator operates isothermally.

- A. Determine the temperature of the working fluid at the exit of the receiver.
- B. Determine the power output for the system for the given collector area.
- C. Determine the system efficiency based on power.
- D. The given direct incident solar represents an average value for an average daylength of 9 hours per day over a year. Using this information determine the energy produced by this system for one year.
- E. Is the system efficiency different based on energy vs the power? Explain your answer.
- F. Neglecting the effects of interest, degradation and usage factors, estimate the capital costs for this system if the produced electrical power cost is 75 USD/MWh over a 20-year lifetime.
- G. If the peak direct incident solar radiation is  $900 \text{ W/m}^2$ , determine the capacity factor for this system using the average information cited in part "c". The average production corresponds to the nominal system capacity.

NOTE: Many of the details that are involved in a CSP system have been removed from this problem, but it illustrates the reason for concentrating solar radiation to increase its flux and reduce the heat transfer area from the receiver. It is a system level analysis based on the energy balance and heat transfer theories, builds on the material in Chapter 1 of the textbook and is intended to get you questioning about the details of the CSP systems. We will learn much more in the coming weeks. For the moment, we are looking for an analysis of given conditions by making rough estimates using given design choices.

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**Homework Assignment #3**

Read Chapter 2.3 to 2.4. (pages 70-78)

Using the information in the text and provided in the Lectures (Calculation of incident solar radiation) Determine the Direct Incident Solar radiation (DNI) on a horizontal surface for a location corresponding to location of your home city for January 15 and July 15 at 10:00, noon, and 15:00 (all solar times) for clear sky conditions. It is suggested that you set up these calculations on an Excel Spreadsheet or a Matlab code.

For January 15, calculate the incident solar radiation on the horizontal surface, the incident angle for 30 min intervals. Plot the values of the incident solar radiation and incident angle as a function of the time of day. Then calculate the incident solar energy, kWh/m<sup>2</sup> per day. Using the incident solar daily value, estimate a yearly incident solar energy value. Compare this value to that for solar tower power feasibility reported in Chapter 1 of your textbook. Would you recommend constructing a solar power tower in your location? (Discuss your result, this is not a yes/no answer and is intended to get you thinking of what the energy value stated in your text is based on)

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**Spring 2025 Semester**  
**Homework Assignment #4**

Consider a receiver tube without protective glass cover. Within the range of solar irradiation, the absorptivity of the receiver surface is 92% emissivity is 20%. In the long wavelength (thermal radiation) range, the emissivity of the receiver surface is 85%. Assume reflectivity of the tube surface is negligible. The tube is made up of stainless steel with 20 W/(m K) thermal conductivity. The inner and the outer diameters of the tube are respectively 66-mm and 70-mm. The outside atmospheric temperature is 17 °C. Convection coefficient between the receiver surface and the outside is 10 W/(m<sup>2</sup>K). Suppose high pressure water flows inside the receiver tube at an average 127°C temperature. Specific heat capacity of the liquid water is 4.24 kJ/(kg K). The convection coefficient between the inner tube surface and the water is 500 W/(m<sup>2</sup>K). Assume concentrated solar radiation arrives uniformly on the receiver tube surface at rates of 5, 10, 20, and 40 kW/ m<sup>2</sup> at 4 different times.

- a) Find the thermal resistances of receiver tube, due to convection at the outer surface, and due to convection between the tube and water.
- b) Define a system that shows all relevant energy interactions for the energy transfer between solar irradiation, water, and outside.
- c) For each of the given irradiation levels, determine the inner and outer surface temperatures of the receiver tube.
- d) Determine the efficiency of the receiver tube defined as energy transferred to the water vs energy incident on the receiver tube for each of the given irradiation levels.

**ME 5680 Applications of Concentrating Solar Thermal Technologies**  
**Spring 2025 Semester**  
**Take Home Exam #1**

**Q1)** In HW3, you have estimated the solar radiation on a horizontal surface at your home location on Jan 15 and July 15. We will make a better estimate of yearly solar irradiation. First state the location, longitude and latitude. Then

- a) find the sunset and sunrise times and variation of solar altitude ( $\beta$ ) and Azimuth Angle ( $\phi_{ss}$ ) from sunset to sunrise for 21<sup>st</sup> day of each month of the year
- b) make a plot of results in part a) like sun path diagram that we covered in lectures during chapter 2 (Handout #8). You do not need to plot the solar times but the variation of angles from sunset to sunrise. If you prefer you can plot all 12-day results in a single plot or you can make separate plot for each day
- c) determine clear-sky direct solar irradiation, in  $W/m^2$ , from sunrise to sunset for each day and make a plot of it.
- d) find the total energy in direct solar radiation for each of the 12 days, in  $MJ/m^2/day$ .

**Q2)** Update your estimate of direct solar radiation to include non-clear days.

- a) Make a search and find out the portion of daytimes that are cloudy for each month for your location.
- b) Assume clear-sky index is  $k_{cc} = 0$  for those cloudy times. Using your results in Q1.d) and result of part Q2.a) Estimate total direct solar radiation available for each month adjusted for cloudy days.
- c) Estimate the total direct solar radiation available for entire year in  $MJ/m^2/year$ .

**Q3)** What is the total amount of water that can be heated each year using the available solar radiation in your area, if

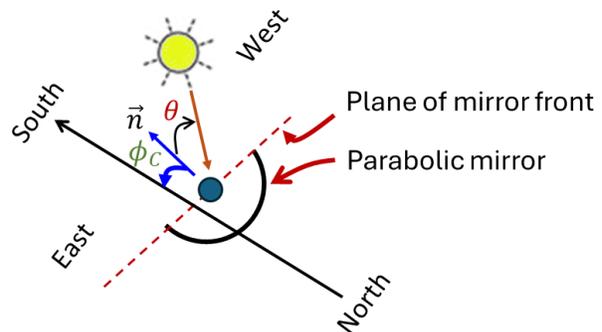
- A parabolic trough concentrating system is available with concentrating factor of 40 and optical efficiency of 60%
- Surface area for collectors is  $400 m^2$  (before concentration).
- We want to heat liquid water from 320 K to 420 K under 10 bar pressure.
- Specific heat capacity of water in this range is  $4.24 kJ/(kg K)$ .
- Efficiency of the receiver (energy passed to the water vs energy received) is 30%.

**ME 5680 Applications of Concentrating Solar Thermal Technologies**  
**Spring 2025 Semester**  
**Takehome Exam 2/Project**

In Exam 1, Q1, you estimated daily variation of solar angles, and incident radiation of a particular day of each month in MJ/m<sup>2</sup>/day. Later you used daily radiation estimates to figure out total radiation each year, MJ/m<sup>2</sup>/year. In the following questions you used the results to figure out the mass of water you can heat from 320 K to 420 K at 10 bar pressure, given 400 m<sup>2</sup> collector area. We will improve estimates of available solar radiation and optical efficiency used in that problem with more precise solutions in this assignment.

**Q1) [30pt]** In chapter 2 (Lecture 6) I gave you eqn (2.30) to calculate incidence angle on a tilted flat plate collector, as follows  $\cos(\theta) = \sin(\Sigma) \cos(\beta) \cos(\phi_{ss} - \phi_{cc}) + \cos(\Sigma) \sin(\beta)$  where  $\Sigma$  is the tilt angle,  $\theta$  is the incident angle between the surface normal and direction of sunlight.

Sketch on the right demonstrates how we can estimate the incidence angle for a simplistic parabolic trough mirror system. We are considering motion only in one direction. In this case, collector angle  $\phi_{cc}$  can be adjusted, It is measured + towards east of south (negative towards west of south). Assume fixed tilt angle  $\Sigma = 37^\circ$ .



Solar irradiation hitting the plane of mirror front at the right angle is  $I_{D, \cos(\theta)}$ . Hence, to maximize energy hitting to the mirror  $\cos(\theta)$  theta should be maximized. Find the optimum collector angle  $\phi_{cc, \text{opt}}$  required to maximize it and determine the corresponding  $\theta_{\text{opt}}$  as a function of solar time for each day and plot it on a  $\theta_{\text{opt}}$  vs time graph. Note, derivative of  $\cos(\theta)$  wrt collector angle  $\phi_{cc}$  will be zero for the max and min values. The second derivative should be negative for the maximum. Then calculate clear-sky direct solar irradiation hitting the collector at right angle, in W/m<sup>2</sup>, from sunrise to sunset for each day like you have done in exam 1. Note  $I_{D, \cos(\theta_{\text{opt}})} = I_{D, \cos(\theta_{\text{opt}})}$ .

**Q2) [15pt]** Similar to Q2 of exam 1, calculate yearly available clear sky radiation in MJ/m<sup>2</sup>/year including the influence of incidence angle. Also calculate the one including the effect of cloudy days in MJ/m<sup>2</sup>/year as you have done in exam 1 Q2. This result, including the incidence angle effect, will be a better estimate than you have done in exam 1.

**Q3) [10pt]** In chapter 3 (Lectures 6-10) we learned about how optical errors are quantified. For parabolic trough concentrators adjustment (canting error) is not a concern since mirror is a single piece controlled by the mounting and tracking system.

However, surface shape error,  $\delta\delta_{SS}$  (due to imperfect profile of the mirror), pointing error,  $\delta\delta_{oo}$  (due to imperfect pointing the mirror system to reach  $\theta_{\theta_{oooooo}}$  that you solved in Q1, and microscopic surface error,  $\delta\delta_{RR}$  due to surface roughness will be significant factors determining optical efficiency of concentrating system. Estimate the efficiency of optical system assuming mirrors have shaping errors given as  $\delta\delta_{SS} = 0.5^\circ$ , pointing errors given as  $\delta\delta_{oo} = 1.5^\circ$ , and surface roughness errors given as  $\delta\delta_{RR} = 0.1^\circ$ .

**Q4) [35pt]** In Chapter 7 (lectures 19-21) we learned how transparent, reflective, and absorptive components are structured and their performance metrics evaluated. Suppose we want to have a low-cost concentrator. The mirrors are made up of 1-mm thick BK7 borosilicate glass with 2 $\mu$ m-thick Al coating for reflectance and the back side of Al coating is painted for protection. The refractive index of the glass is  $n_{ngg} = 1.516$ , it has 4% reflectivity and absorptivity of 0.3% both in solar radiation range. Pure Al has refractive index of  $n_{nAcc} = 1.373$ .

- a) [25pt] Assuming no anti-reflective layers, estimate overall reflectance,  $\rho_{\rho_{ss}}$  of this mirror system in the solar radiation range (0.28  $\mu$ m to 2.5  $\mu$ m wavelength range). Assume incident radiation first pass through the glass with first reflection (cant be used in concentrating system), absorbed in the glass, remaining portion hits the Al reflector (partially absorbed remaining reflected), reflected beam passes through the glass subject to second absorption. Note spectral distribution of solar ground level irradiation is given [ASTM-G173-03.pdf](#) posted in Canvas Module for week-11 ([astmg173 | lambda.xls](#) has all numerical values of spectral irradiation). There is also a graph showing spectral reflectivity of the Al (you can roughly read values of reflectance from the graph for your calculations). Note the posted spreadsheet has data with 0.5nm to 5nm wavelength intervals. Recommended wavelength intervals for solar performance metrics is 5nm. You can down sample the data or use a linear interpolation function to get the values at your desired wavelengths.
- b) [10pt] If one wishes to add anti-reflective coatings what would be required thickness and refractive index of anti-reflective layers. Note you will need one at top (glass and air interface) and another at the bottom (glass-aluminum interface). Assume target wavelength to cancel reflection is 500 nm.

**Q5) [10pt]** Assume concentrating factor is 40 and the total surface area available for mirrors (before concentration on the plane of mirror front) is 400 m<sup>2</sup> as in exam 1. Considering the available solar energy after incidence angle and cloudy-day effects that you found in Q2, and optical losses in Q3 and reflection losses in Q4, what is the solar energy on the receiver. If you define optical efficiency as the energy on the receiver in relation to direct solar energy available locally (after the cloud effects but before the incidence angle effect), what is the optical efficiency of this system. Note if you measure

both available energy and energy on the receiver in MJ (rather than energy flux MJ/ m<sup>2</sup>)  
you can find the answer without finding the required surface area of receiver. Otherwise,  
you may need to find the receiver surface area from the concentration factor.