General instructions

Software for the online experiment

- On clicking the START EXAM button, a window will popup to start screen recording.
- You will have to share your entire screen. Sharing just a window or a tab will not allow you to access the simulations.
- Only after the screen recording starts, you will be able to see the simulation.
- After permitting to share your screen, a dialogue box at the bottom will appear with two options - "Stop sharing" and "Hide". Click on "Hide" to hide this dialogue box.
- There will be options for refreshing the simulation and switching between the 2 simulations
- Once the examination ends, please click on the finish button.
- Ending screen sharing prematurely may immediately result in revoking your authorization.
- **Your screen is being recorded all the time. Any unauthorized activity such as opening another Window/Tab/Program etc. will result in disqualification.**
- If you accidentally click the finish button or your system crashes, you may log in again to finish the exam. Later this will be reviewed through logs and may result in disqualification if you log out without any valid reason.
- If the simulation freezes, please try the following: 1. Click the "REFRESH" button (next to the "FINISH" button) 2. If the "REFRESH" button is also unresponsive, try refreshing the website (refresh icon next to the URL bar) 3. If point 2 did not work, close the browser and login again. Note that this will be reviewed post exam.
- Sometimes, there maybe overlap between controls (and inputs) and the graphics region. In such a case: 1. Please zoom out to 100% (default zoom) (Ctrl+ 0). 2. Press the "REFRESH" button (next to the "FINISH" button). 3. Now, you can zoom back without overlap.

Repeat the above process if the overlap repeats.

Before the exam

- For the experiment exam, three A4 size envelopes are marked as Q1, Q2, and General instructions.
- You will also find your student code written on the envelope.
- You must not open the envelopes containing the problems before the sound signal indicating the beginning of the competition. The beginning and end of the examination will be indicated by a sound signal.
- There will be announcements by the supervisor at 11:55(Before the exam begins), 12:00(To indicate the start of the exam), 16:30(Before the final sound signal), and 17:00(To indicate the end of the exam).

During the exam

- Five minutes prior to the scheduled time of the examination (11:55) the supervisors will send a suitable signal by ringing a bell etc to open the envelopes. At this time, you may log in to the exam portal.

- **Your screen is being recorded all the time. Any unauthorized activity such as opening another Window/Tab/Program etc will result in disqualification.**
- You should make sure to have a complete set of questions, answer sheets, and general instructions, marked with your student code on them.
- The exam starts at 12:00 IST.
- Dedicated answer sheets are provided for writing your answers. Write your answers into the appropriate tables, boxes, or graphs on the corresponding answer sheet (marked A). For every problem, there are extra blank working sheets for carrying out detailed work (marked W). Be sure to always use the working sheets that belong to the problem you are currently working on (check the problem number in the header). If you have written something on any sheet which you do not want to be graded, cross it out. Only use the front side of every page.
- In your answers, try to be as concise as possible: use equations, logical operators, and sketches to illustrate your thoughts whenever possible. Avoid the use of long sentences.
- In the tasks, error estimation is **not** required. You should decide on the appropriate number of data points or measurement repetitions unless specific instructions are given. Please give an appropriate number of significant figures when stating numbers.
- Often, you may be able to solve later parts of a problem without having solved the previous ones.
- A list of physical constants is given on the next page.
- You are not allowed to leave your working place without permission. If you need any biological break, please draw the attention of a team guide by raising your placard.
- At 16:30 hrs, the supervisors shall make a suitable indication that the examination will end in thirty minutes.
- A final signal will be given at 17:00 indicating the end of the examination.

At the end of the exam

- After the final signal is received at 17:00, Students should stop writing immediately and place all the answer scripts and working sheets even if they are empty in the designated envelopes. For example, the envelope for Q1 must contain only the answer scripts and working sheets for Q1. Place question papers and general instructions in the third envelope marked as general instructions.
- Leave your writing equipment on the table.
- Wait at your table in silence until your envelopes are collected. Once all envelopes are collected your guide will escort you out of the examination area.

Physical constants

Acceleration due to gravity	g	=	$9.81 m \cdot s^{-2}$
Boltzmann constant	k_B	=	$1.38 \times 10^{-23} J \cdot K^{-1}$
Current Mass of the Sun	M_s	=	$2.00 \times 10^{30} kg$
Current Radius of the Sun	R_s	=	$7.00 \times 10^{8} m$
Magnitude of the electron charge	e	=	$1.60 \times 10^{-19} C$
Mass of the electron	m_e	=	$9.11 \times 10^{-31} kg$
Mass of the proton	m_p	=	$1.67 \times 10^{-27} kg$
Mass of the neutron	m_n	=	$1.67 \times 10^{-27} kg$
Permeability of free space	μ_0	=	$1.26 \times 10^{-6} T \cdot m \cdot A^{-1}$
Permittivity of free space	ϵ_0	=	$8.85 \times 10^{-12} F \cdot m^{-1}$
Planck's constant	h	=	$6.63 \times 10^{-34} J \cdot s$
Avogardo Constant	N_A	=	$6.02 \times 10^{23} mol^{-1}$
Stefan-Boltzmann constant	σ	=	$5.67 \times 10^{-8} W \cdot m^{-2} \cdot K^{-4}$
Universal gas constant	R	=	$8.31 J \cdot mol^{-1} \cdot K^{-1}$
Universal Gravitational constant	G	=	$6.67 \times 10^{-11} N \cdot m^2 \cdot kg^{-2}$
Wien's constant	b	=	$2.90 \times 10^{-3} m \cdot K$
ln 2	$\approx$		0.69
ln 3	$\approx$		1.10
ln 10	$\approx$		2.30
Base of the Napierian logarithm e	$\approx$		2.72

Magnetic Black box:[1]

Smartphones use Hall effect-based magnetometers to measure the magnetic field in its vicinity. The magnetometer measures all three components of the magnetic field. The magnetometer sensor is located on the circuit board of the phone and is not visible from outside.

Magnetic field of a magnet
Figure 1 shows a small bar magnet with half length d and the dipole moment M.

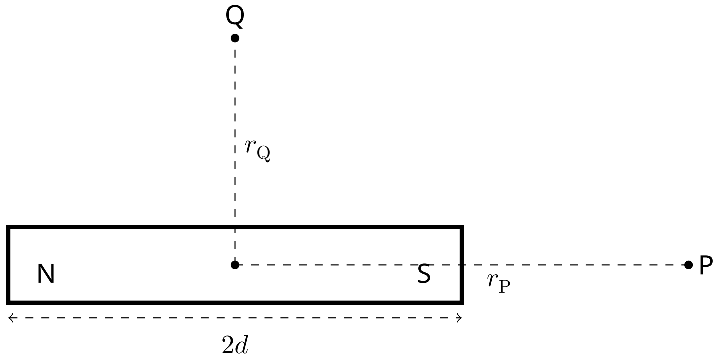

Figure 1

The magnitude of the magnetic field of a bar magnet in the axial direction at point P (B_{axial}) and at point Q on its perpendicular bisector ($B_{\text{equatorial}}$) is given by the following formulae

$$B_{\text{axial}} = \frac{\mu_0}{4\pi}\frac{2Mr_{\text{P}}}{(r_{\text{P}}^2 - d^2)^2} \quad (1)$$

$$B_{\text{equatorial}} = \frac{\mu_0}{4\pi}\frac{M}{(r_{\text{Q}}^2 + d^2)^{3/2}} \quad (2)$$

where μ_0 is the permeability of free space ($\mu_0/4\pi = 10^{-7}\text{NA}^{-2}$), and $r_{\text{P}}, r_{\text{Q}}$ are the distances between the center of the magnet to the points where the field is measured. For the given problem, consider the magnet to be a point dipole ($d \ll r_{\text{P}}, r_{\text{Q}}$).

Click on "EQ1-Magnetic Black Box" link in the exam portal for the experimental exam.

About the simulation on the screen:
You will see a canvas with a white background in the form of a grid on the screen. This grid canvas is a part of the vertical plane where the experiment is being carried out. There are four objects on the canvas:

1. a smartphone
2. a magnet in blue (S) and red (N) color
3. a dark shaded hollow pipe with uniform thickness
4. a calibrated scale, which can be activated by clicking the 'SHOW/HIDE SCALE' button.

Intergrid spacing on the grid canvas is 1 cm.

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[1] Chandan Relekar (IISc, Bangalore), Siddhant Mukherjee (The University of Cambridge, UK), Siddharth Tiwary (IIT Powai, Mumbai), Charudutt Kadolkar (IIT Guwahati), Praveen Pathak (HBCSE-TIFR, Mumbai), were the principal authors of this problem. The contributions of the Academic Committee and the International Board are gratefully acknowledged.

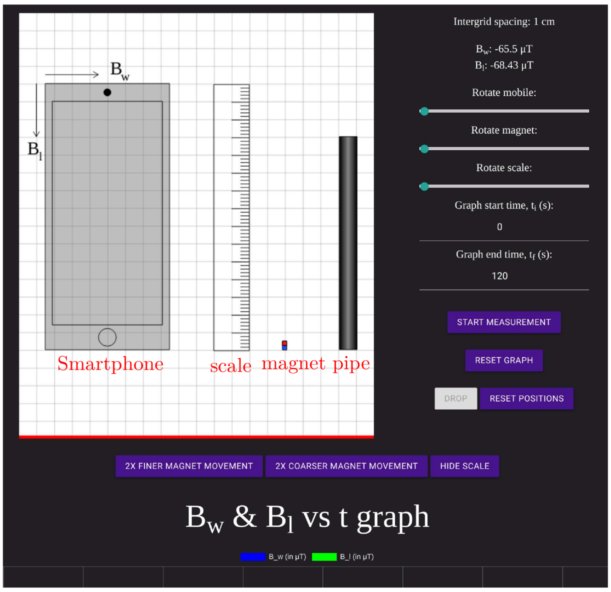


Figure 2: Screenshot of the simulation

The set up:
The objects can be moved by holding and dragging the mouse. Smartphone, scale, and magnet can also be rotated in the plane. The rotation control slider is available in the right panel. You can drag the slider to change the orientation. For a better control, after clicking on the slider, you can use arrow keys to rotate an object.
There is a magnetometer inside the phone which measures the magnetic field of the magnet in its vicinity. The exact location of the magnetometer in the phone is not given to you. Depending on the location of the magnetometer, the right panel displays the components B_w and B_l of the magnetic field of the magnet measured by the smartphone along its width and length, respectively, as shown in Fig 2. Component B_w points to the right for the default position (portrait/vertical orientation) of the phone. Component B_l points downwards along the length of the phone.

The measurement:
When you click on 'START MEASUREMENT' you can also see the graph of variation of B_w and B_l as a function of time. 'RESET GRAPH' will erase all the values recorded in this graph. When you move the cursor over the curve in the graph obtained, you can see the value of the data point. A portion of the graph can be zoomed in by inserting the time in the "Graph start time (t_i)" and the "Graph end time (t_f)" fields.

Smartphones may get damaged if they are exposed to high magnetic field. To prevent this, if the net magnetic field value measured by the smartphone exceeds 6500 μT, the measurement will stop and you will see a warning on the right panel 'Maximum Magnetic field exceeded.' Measurement is restored as soon as the magnet is moved away from the phone at a sufficient distance.

Further features:
The magnet can be moved by keyboard arrow keys in up-down and left-right directions. For this, click anywhere on the canvas. A finer/coarser movement of the magnet can be achieved by clicking '2X FINER MAGNET MOVEMENT/2X COARSER MAGNET MOVEMENT'. With each clicking of these buttons, the movement will become two times finer/coarser. The buttons will grey-out when the maximum coarse/finer level is reached.

Gravity is in the downward direction, towards the bottom of the screen. The floor is indicated by a red line. Consider all the objects in the plane of the screen only. More information about the pipe is given before the part (B).

Consider the magnet to be held in a stationary position when you place it anywhere on the screen. Clicking on the "Drop" button will release the magnet and it will start descending. Note that the magnet can be dropped only after clicking the 'START MEASUREMENT' button. The 'RESET POSITION' button will bring back the magnet to the position from where it was dropped last. Objects can be moved outside the Canvas if needed.

In this experiment, consider the magnet to be a point dipole.
Note that there is no error estimation required in this question.

A.1	Obtain the location of the magnetometer on the phone. To help you answer this part in the answer sheet, a finer grid is made inside the schematic diagram of the phone. Intergrid spacing in the finer grid is 2 mm. Indicate the location of the magnetometer by drawing "$\otimes$" in the smartphone at an appropriate place.	1pt

A.2	Plot a suitable linear graph and obtain the dipole moment of the magnet from the graph. Fill in the table for the recorded data of the method you have employed.	2.3pt

A hollow nonmagnetic vertically held pipe of finite uniform thickness is given on the screen. For the magnet to be dropped inside the pipe, the magnet should be aligned with the axis of the pipe properly. The "DROP" button will release the magnet in the vertical plane. The motion of the magnet inside the pipe cannot be viewed. Assume that when the magnet is dropped inside the pipe, it doesn't tilt or rotate as it descends. The pipe consists of three distinct sections: one section is made of wood (W), another section is made of aluminum (Al) having electrical conductivity $= 3.77 \times 10^7 \Omega^{-1}\mathrm{m}^{-1}$, and the remaining section is made of copper (Cu) having electrical conductivity $= 5.96 \times 10^7 \Omega^{-1}\mathrm{m}^{-1}$. These three different materials may/may not be in this order. If the magnet is dropped vertically (say along the downward y-axis), the fall of the magnet is governed by

$$m\ddot{y} = mg - k\dot{y} \tag{3}$$

where m is the mass of the magnet, g is the acceleration due to gravity ($g = 9.8\mathrm{m/s^2}$), and k is the damping constant due to the generation of the eddy current in the pipe. The damping constants for the wooden, aluminum, and the copper sections are zero, k_{Al}, and k_{Cu}, respectively. Drop the magnet inside the pipe following these steps:

1. Position the phone, the magnet and the pipe suitably.
2. Click the "Start Measurement" button.
3. click the "DROP" button.

The magnetometer can not measure very small magnetic field produced due to the eddy current in the pipe. As the magnet descends through the pipe, a graph of B_w and B_l as a function of time may be seen on the screen.

B.1	From the graph of the magnetic field vs time shown on the screen, find out the sequence of sections of different materials in the pipe. Indicate your answer by writing the number next to the material of the pipe considering them in order from top to bottom: 1 for the top section, 2 for the middle section, and 3 for the bottom section.	0.3pt

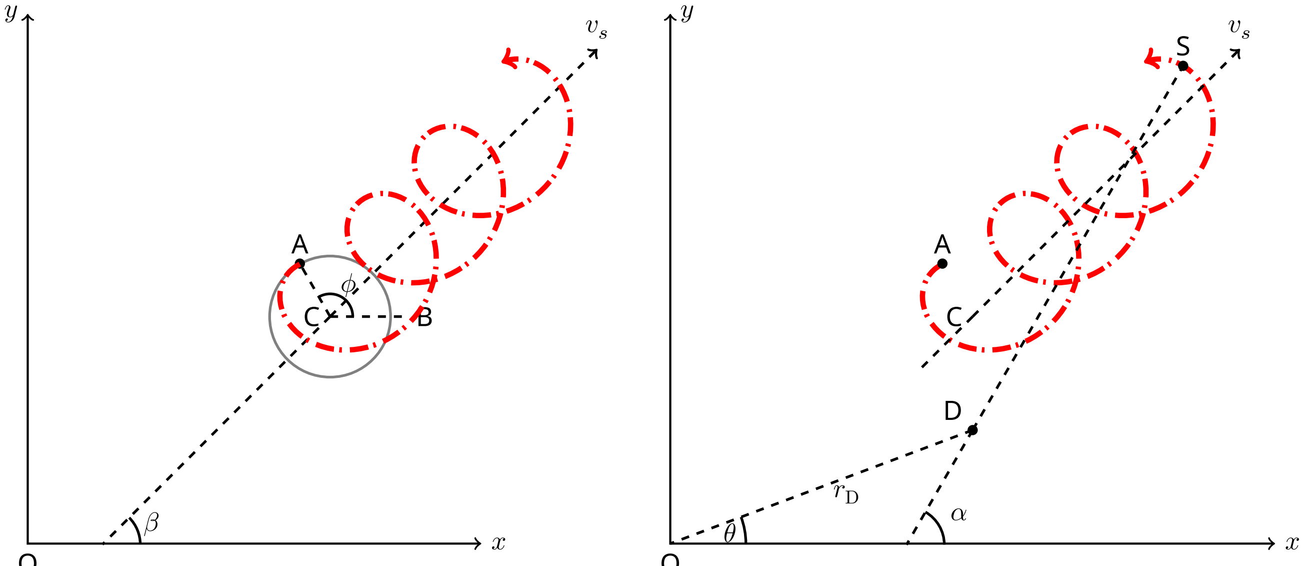
B.2	Determine the terminal velocity of the magnet in the Aluminium section of the pipe, plotting a suitable linear graph. A canvas grid similar to the simulation screen is given in the answer sheet. Draw the schematic smartphone, pipe, and magnet to the exact locations and orientations you have used to obtain the data for this part. Use a box to indicate the Phone. Fill tables with the relevant data set you are using for plotting the graph. Determine the length of the Aluminium section of the pipe. You may/may not use a graphical method for measuring the length of the aluminium section of the pipe. If you are using a graph/data set to determine the length, use the extra columns in the table to report the relevant data set.	2.6pt

B.3	Determine the terminal velocity of the magnet in the copper section of the pipe, plotting a suitable linear graph. Determine the length of the copper section of the pipe. You may/may not use a graphical method for measuring the length of the copper section of pipe. If you are using a graph/data set to determine the length use the extra columns in the table to report the relevant data set.	2.2pt

B.4	Determine the length of the wooden section of the pipe. You may/may not use a graphical method for measuring the length of the wooden section of pipe. If you are using a graph/data set to determine the length use the extra columns in the table to report the relevant data set.	1.6pt

Acoustic blackbox[1]

A sound source is moving on a circle of fixed radius R in x-y plane with a constant angular speed ω. The circle is also moving with a uniform velocity v_S which makes an angle β ($0^\circ < \beta < 90^\circ$) with the x-axis. Figure 1 shows the trajectory of the source in red color dash-dotted line. At time $t = 0$, the center of the circle is at C, with coordinates $(\mathrm{X_C}, \mathrm{Y_C})$, the position of the source is given by vector $\vec{CA}$ from C. In addition, the source S starts moving anticlockwise (counterclockwise) direction (see Fig. 1) simultaneously emitting a sound of frequency f_0 at time $t = 0$. Vector $\vec{CA}$ makes an angle ϕ with respect to the x-axis at $t = 0$ ($\angle BCA = \phi$ in Fig. 1(a)). A detector D is kept in the same plane (x-y) such that its distance from the origin and the angle which the position vector makes with the x-axis are r_D and θ respectively (in Fig. 1(b)). Line joining the detector D and the source S makes an angle α with the x-axis. All the motions of the source and the detector are in the x-y plane only. The speed of sound, c is 330m/s. Also, the net speed of the source is smaller than c.



(a) Initial location of the source. (b) Trajectory of the source.

Figure 1

The sound emitted by the source is detected by the detector at time t with frequency $f(t)$. The simulation displays the detected frequency $f(t)$.

A.1	Obtain the equation of the trajectory $(x(t), y(t))$ of the source in terms of β, ϕ, v_s, and the other relevant quantities.	0.2pt

Click on "EQ2- Acoustic Black box" on the exam portal for the experimental exam.

[1] Siddharth Tiwary (IIT Powai, Mumbai), Siddhant Mukherjee (The University of Cambridge, UK), Chandan Relekar (IISc, Bangalore), Charudutt Kadolkar (IIT Guwahati), Praveen Pathak (HBCSE-TIFR, Mumbai), were the principal authors of this problem. The contributions of the Academic Committee and the International Board are gratefully acknowledged.

About simulation:
There are two parts to the simulation. The upper part of the panel is the input panel for the detector's parameters and the lower part of the panel is the display of the graphical output of the frequency ($f(t)$) detected by the detector at time t.

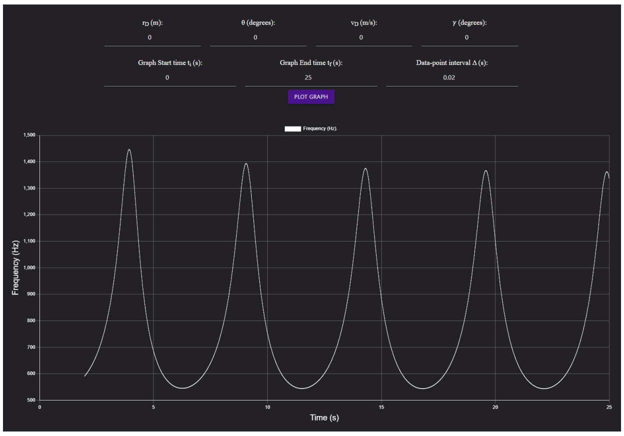


Figure 2:Default simulation screen

You can change the detector's position by entering the values of r_D and θ in the input panel. If you change the value in the panel, you need to click the "PLOT GRAPH" to view the changed output of $f(t)$. You can change the interval at which data is collected in the field "Data-point interval Δ". Note that this interval can only be a multiple of 0.001s.
You can set the detector in uniform motion by entering the speed v_d and the angle γ, which velocity vector $\vec{v}_d$ makes with the x-axis. Again you have to click the "PLOT GRAPH" button to view the output for the changed parameters.
Once the PLOT GRAPH button is clicked, a graph will be displayed for the interval "Graph Start time (t_i)" to "Graph End time (t_f)". In Fig. (2), the panel displays the graph for 0 to 25 s.

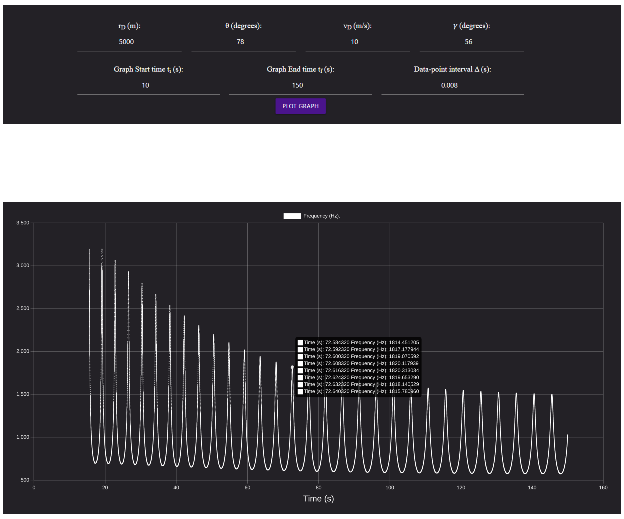


Figure 3: Simulation screen for the changed input values

Graph Start and End time input can also be used to zoom in on a portion of the graph. To illustrate, Fig. (3) shows the output for the case when the detector is placed at 5000 m at angle 78°. The graph output is plotted between 10-150 s. Data is collected at every 0.008 s. When you place the cursor over the curve's data point, it shows the values of the data points. Since the time interval is very small, placing the cursor over the curve may show the values of multiple data points. In Fig. (3), eight data points are shown. **Caution:** If you keep the data point interval (Δ) very small (say 0.001) and plot it for a long time interval (say Graph Start time($t_i = 0$) to Graph End time($t_f = 25s$)), simulation will take a long time and may freeze depending on the capacity of your machine. If you are stuck in such a situation, follow the steps given in the General Instructions. Very small Δ can be used only for a small time interval of the plot. While running simulation maximum number of data points that simulator can plot is 25000, irrespective of Graph End time (t_f (s)).

Try various values of the detector parameters in the simulation and carefully observe the output. Use the output of the graph for the calculation in the following parts. You may use graph papers in any part if required.

A.2	Keep the detector stationary at $r_{\mathrm{D}} = \theta = 0$ in the simulation. Observe the output graph of $f(t)$ between the graph start and end time 5 s and 55 s respectively. Tabulate all the minima ($f_{\min}$ and the corresponding time t) in the range. Plot $f_{\min}$ vs t.	1.2pt

A.3	Obtain an expression for the minimum frequency that the detector will eventually detect if kept stationary. Express your answer in terms of v_s, ω, R, and the relevant variables.	1.0pt

You will be using various input values in the panel to obtain the answers for the following parts. In the table given on page A2-4, report the various values of $r_{\mathrm{D}}, \theta, v_{\mathrm{D}}, \gamma, t_i, t_f,$ and Δ which you have used to obtain the quantity or any intermediate equation. Also, mention the corresponding quantity or that equation against the input values.

Any formulae/equations in solving this part must be mentioned in the working sheets in detail. Marks will not be awarded solely based on the final answer. If you want to use a graph, mention the graph paper number on the answer sheet. Note that there is no error estimation required in this question.

Solve the next four questions in any order that you find appropriate.

A.4	Obtain the source's initial coordinates $(X_{\mathrm{A}}, Y_{\mathrm{A}})$ i.e. coordinates of the point A at time $t = 0$ in meters.	1.4pt

A.5	Obtain the values of f_0, ω, R, v_s.	2.1pt

A.6	Obtain the value of β in degrees.	2.0pt

A.7	Obtain the source's initial center coordinates $(X_\mathrm{C}, Y_\mathrm{C})$ i.e. coordinates of the point C in meters.	2.1pt