MPI for Ornithology

Acoustic Tracking

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This is version of April 26, 2013. This file is still under construction.

Contents

1. Principle of Acoustic Tracking

Acoustic tracking localizes the three-dimensional position of a sound source based on simultaneous recordings of this sound source on multiple microphones. We use a four-channel recording system (four microphones) arranged in a flat star-shaped to track the positions of flying bats.

2. Recording System

We use a four-channel Avisoft UltrasoundGate 416H with four Avisoft UltrasoundGate CM16/CMPA microphones (Avisoft Bioacoustics, Berlin, Germany) to record bat calls. The microphones fixed to an inverted-T-shaped array that can be mounted on a tripod. On the T-shaped array, the microphones are arranged in a symmetrical flat star, with one central microphone (M0) and three peripherial microphones (M1 - M3). The distance between the central and each peripheral microphone is 60 cm, the angle between the 'arms' of the star is 120°.

3. Analysis Software

The Acoustic Tracking System uses two user-callable software programs, `actrack_main` and `pathbuilder`. All files that are required for each of the two analysis programs are kept within a separate main folder, which contains the main program and one folder with all required subfunctions. All files and folders must be kept in this order.

- **actrack_main** `actrack_main.m` calculates the three-dimensional positions based on call sound recordings.
- **PathBuilder** `PathBuilder.m` provides a praphical user interface (GUI) to visualise the spatial postions and the call spectrogram for each position. The user can delete outliers, connect positions to flight paths, add species names and do some basic path analysis.

3.1. Calculate 3D-positions: actrack_main.m

The function `actrack_main.m` calculates the spatial positions based on wav-files and is in the folder TOAD_3D. It is called by typing the function name at the Matlab prompt. After selecting a folder with sound recordings, it will process all sound recordings. It will detect the recorded calls and calculate the difference in the arrival time of each call at the foIt requires XXX input arguments:

3.2. Visualise and reconstruct flight pahts: PathBuilder.m

The function `PathBuilder.m` is in the folder PathBuilder. It is a graphical user interface that is used to visualise the spatial positions of the bats and to combine them into flight paths.

4. Definitions

For the Acoustic Tracking Software to work properly, some definitions are required. They are described here; read them carefully and adhere to them.

4.1. Data Files

Data files consist of the recorded sound files (*.wav), the recorded climate data (*.csv) and the calculated spatial positions and flight paths (*.mat). These files will be stored in certain folders (see next section below) and require a certain file name.

- **Sound Files (*.wav)** The sound files are recorded by Avisoft Recorder Software and stored in separate folders per recording session (see below for folder structure). The filename is generated automatically by Avisoft Recorder and contains the microphone number, recording date, recording time and a continuous recording number. These four blocks of information always make up the **first four parts of the filename**:

  `MicNum_FileDate_FileTime_FileNum.wav.`

  Note about the FileDate and FileTime: The **FileDate** is the date at which the sound was recorded. If this is past midnight, the FileDate is one day after the **SessionDate**, which is the date of the folder in which all sound recordings are stored. We use the SessionDate to group all recordings of one recording session (e.g., one night), and we always use the SessionDate to find other matchin information for these recordings, such as the climate data or information on the setup position. The FileDate is more or less only an identifier for this sound recording. The **FileTime** is the start time of the sound recording and is taken from the computer's time setting. So please adjust your computer's clock to the correct time zone, and match the time of the Kestrel Weather Meter.

  When playbacks are conducted, we also add the filename of the playback file and its absolute starttime:

  `MicNum_FileDate_FileTime_FileNum_PlayFile_PlayTime.wav.`

  During analysis, the wav-files will be band pass filtered and the filter frequencies will be added to the filename. If no playbacks had been conducted, the filename after filtering has the structure:

  `MicNum_FileDate_FileTime_FileNum_HPfreq_LPfreq.wav.`

  If playbacks had been conducted, the filename after filtering has the structure:

  `MicNum_FileDate_FileTime_FileNum_PlayFile_PlayTime_HPfreq_LPfreq.wav.`

Thus, the final filename can consist of up to 8 blocks of information, which are always separated by **underscores**. Within each block of information, underscores are NOT allowed. Except for the playback filename, the number of digits for each block of information is always the same, as follows:

`MicX_YYYY-MM-DD_HH-MM-SS_NNNNNNN_[Playback-file]_HHMMSS_HPxx_LPxxx.wav`.

(X = mic number, Y = year, M = month, D = day, M = minute, S = second, N = automatic Avisoft file numbering with 7 digits, x: frequency in kHz).

For example, this is an filename without playbacks and before filtering:

`Mic1_2013-07-14_22-17-23_0000134.wav`.

After filtering between 30 and 90 kHz, the filename looks like:

`Mic1_2013-07-14_22-17-23_0000134_HP30_LP090.wav`.

With playbacks, the name and start time of the playback file is added:

`Mic1_2013-07-14_22-17-23_0000134_PipPyg-Search-003_221728.wav`.

Filtering this file between 20 and 120 kHz yields:

`Mic1_2013-07-14_22-17-23_0000134_PipPyg-Search-003_221728_HP20_LP120.wav`.

See Fig. 4.1 for how to setup the Avisoft Recorder Software to obtain the correct filename.

- **Climate Data (*.csv)** The climate data are recorded by the Kestrel Weather Meter. At the end of each recording session, the climate data is downloaded with the Kestrel Interface and stored as one *.csv-file per recording session in the climate folder. The filename has to contain the date and the number of the tracking system number (to identify the correct climate files when multiple tracking systems are used at the same day). The filename thus is defined as:

  `climate_YYYY-MM-DD_S.csv`.

  (S = system number).

- **Spatial Postions and Flight Paths (*.mat)** These files are saved by the Acoustic Tracking analysis programs `actrack_main.m`. The filenames are automatically derived from the sound files and are defined as:

  `YYYY-MM-DD_HH-MM-SS_NNNNNNN.mat`.

4.2. Data Folders

All Acoustic Tracking data have to be in one single folder (e.g., actrackdata). Within this folder, three subfolders are needed, which are called **climate**, **path**, and **wav** (Fig. 4.2).

- **Climate folder** The `climate` folder stores the weather data from which the sound speed is calculated. Weather data are recorded by the Kestrel weather meter and is one file per tracking session (i.e., one evening).

tt

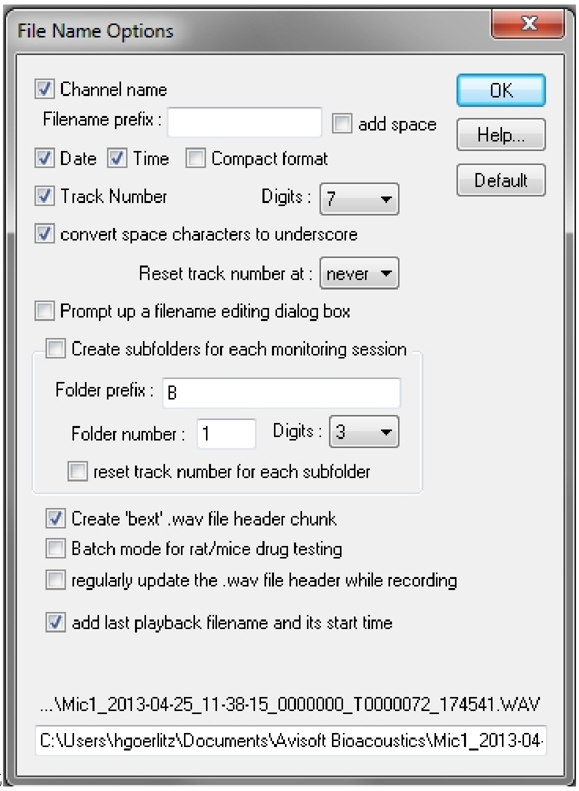

Fig. 4.1.: Avisoft Filename Dialog. Tick 'Channel Name', 'Date', 'Time' and 'Track Number' to include this information in the filename. Set the number of digits for the track number to 7, and tick 'convert spaces to underscore' so that each block of information is separated by an underscore. Also tick 'Create bext .wav file header chunk.
CAUTION: 'add last playback filename and its start time' should ONLY be ticked when playbacks are conducted. If this box is ticked, but no playback are conducted, Avisoft recorder will add the name of the previous, old playback file to the filename of the recorded sound, no matter how long ago this playback happened.

- **wav** The `wav` folder stores the sound recordings (*.wav files), which were recorded by the Avisoft Recorder Software. Recordings are stored in separate folders per tracking session. For each new tracking session, make a new folder named with the date of the recording session in this format:

  `YYYY-MM-DD_S`.

  (Y = year, M = month, D = day, S = session/station).

  Select this folder as the Base Directory in the Configuration Dialog of Avisoft Recorder Software. Avisoft Recorder will then save the recorded wav-files of all four channels in this folder.

- **path** The `path` folder stores the 3D-positions and flight paths (*.mat files). 3D-positions are calculated by actrack_main.m, and flight paths by PathBuilder.m. Like for the wav-files, positions and paths are stored in separate folders per tracking session. These folders will be generated automatically when the positions are calculated by actrack_main.m and have the same format:

  `YYYY-MM-DD_S`.

  (Y = year, M = month, D = day, S = session/station).

```
actrackdata
|
|-- climate
|     climate_2013-07-14_1.csv
|     climate_2013-07-15_1.csv
|     climate_2013-07-15_2.csv
|     climate_2013-07-15_3.csv
|     climate_2013-07-16_1.csv
|
|-- path
|   |
|   |-- 2013-07-14_1
|   |     3D-position-file_1.mat
|   |     3D-position-file_2.mat
|   |     ...
|   |
|   |-- 2013-07-15_1
|   |-- 2013-07-15_2
|   |-- 2013-07-15_3
|   |-- 2013-07-16_1
|   |...
|
|--wav
    |
    |-- 2013-07-14_1
    |     Mic1_wav-file-1.wav
    |     Mic1_wav-file-2.wav
    |     ...
    |     Mic2_wav-file-1.wav
    |     Mic2_wav-file-2.wav
    |     ...
    |     Mic3_wav-file-1.wav
    |     Mic3_wav-file-2.wav
    |     ...
    |     Mic4_wav-file-1.wav
    |     Mic4_wav-file-2.wav
    |     ...
    |
    |-- 2013-07-15_1
    |-- 2013-07-15_2
    |-- 2013-07-15_3
    |...
    |-- 2013-07-16_1
    |...
```

Fig. 4.2.: Required folder structure for the Acoustic Tracking programs.

5. Theory and Mathematics of Acoustic Tracking

5.1. Definitions

Distances and TOAD We define the difference of the signal arrival times (TOAD, τ_i) at the reference receiver (R_0) and any peripheral receiver (R_i) as the arrival time at the reference receiver (t_0) minus the arrival time at the peripheral receiver (t_i) (Fig. 5.1):

$$\tau_i = t_0 - t_i \tag{5.1}$$

Likewise, we define the difference in the distances that the signal travels from the emitter to the receivers as (d_0 is the radius r from the central microphone to the emitter):

$$\begin{aligned} \delta_i &= d_0 - d_i \\ \delta_i &= r - d_i \end{aligned} \tag{5.2}$$

It is: $d = c \cdot t$. Thus, we obtain the travel-distance-difference from the TOAD:

$$\begin{aligned} \delta_i &= t_0 \cdot c - t_i \cdot c \\ &= c \cdot (t_0 - t_i) \\ \delta_i &= c \cdot \tau_i \end{aligned} \tag{5.3}$$

Thus, the distances to the peripheral microphones can be calculated from the radius and

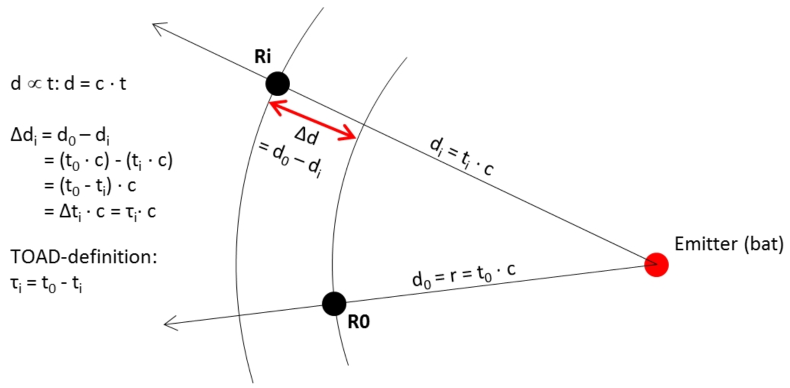

Fig. 5.1.: TOAD Definition. The difference in sound travel time from the emitter to both receivers is proportional to the difference in sound travel distance.

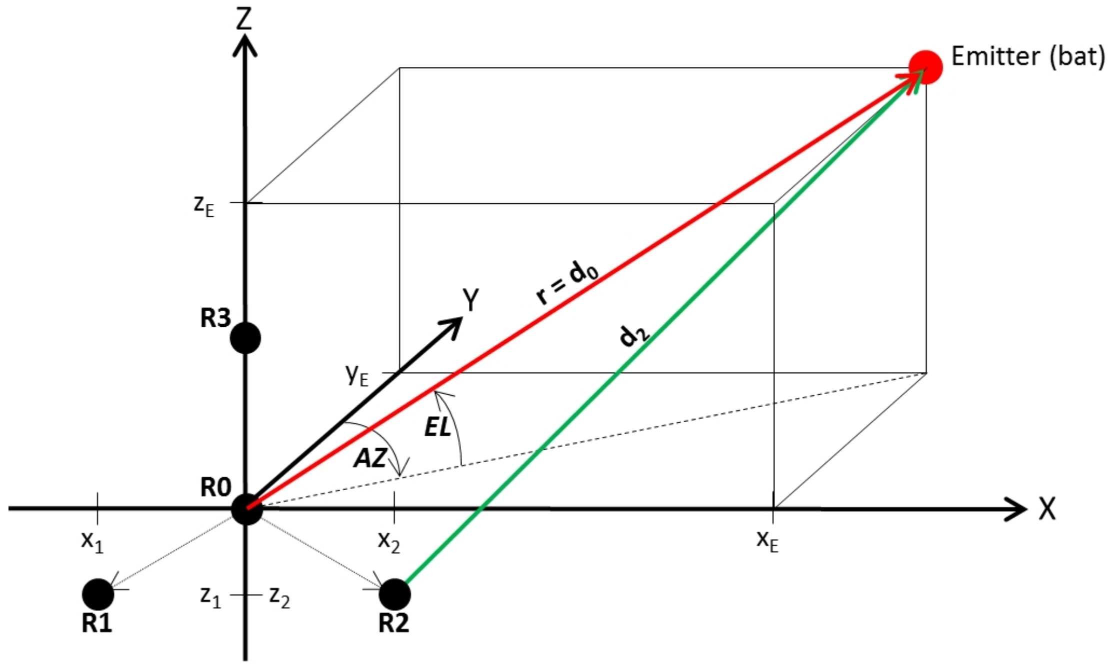

Fig. 5.2.: Star-Array and Coordinate System

the TOADs:

$$d_1 = r - c \cdot \tau_1 \tag{5.4}$$
$$d_2 = r - c \cdot \tau_2 \tag{5.5}$$
$$d_3 = r - c \cdot \tau_3 \tag{5.6}$$

Coordinate system We will use both a cartesian and a spherical coordinate system to express the positions of receivers and emitter (Fig. 5.2). The azimuth, AZ, is definded as the counterclockwise angle from the positive Y-axis. The elevation, EL, is defined as the upward angle from the X-Y-plane. The radius, r, is the distance from the origin. The conversion between Cartesian and spherical coordinates thus is:

$$x_E = r \cdot sinAZ \cdot cosEL \tag{5.7}$$
$$y_E = r \cdot cosAZ \cdot cosEL \tag{5.8}$$
$$z_E = r \cdot sinEL \tag{5.9}$$

5.2. Calculate TOADs from sound recordings

5.3. Calculate emitter postion from TOADs

Distances between emitter and receiver 1 The vector from one point to another point in 3D-space is: $\vec{R_2E} = \vec{R_2} - \vec{E}$ (Fig. 5.2). The length of the vector, i.e., the distance between both points, is calculated from their coordinates:

$$|\vec{d_i}| = sqrt((x_E - x_i)^2 + (y_E - y_i)^2 + (z_E - z_i)^2) \tag{5.10}$$

Thus, for all three peripheral receivers it is:

$$d_0^2 = r = (x_E - x_0)^2 + (y_E - y_0)^2 + (z_E - z_0)^2 \tag{5.11}$$
$$d_1^2 = \quad (x_E - x_1)^2 + (y_E - y_1)^2 + (z_E - z_1)^2 \tag{5.12}$$
$$d_2^2 = \quad (x_E - x_2)^2 + (y_E - y_2)^2 + (z_E - z_2)^2 \tag{5.13}$$
$$d_3^2 = \quad (x_E - x_3)^2 + (y_E - y_3)^2 + (z_E - z_3)^2 \tag{5.14}$$

Receiver positions We use a planar symmetrical receiver array: the receivers are positioned in one plane and are arranged in a mirror-symmetrically relative to one axis. Three peripheral receivers (R_1, R_2, R_3) are placed with the same distance around a central reference receiver (R_0). The central receiver R_0 and the receiver R_3 define the mirror axis. R_1 and R_2 are arranged symmetrically on the left and right of the mirror axis (Fig. 5.2). The coordinate system is defined so that the receivers are in the X-Y-plane, R_0 is the origin, the mirror axis is the Z-axis with R_3 having positive z-values, and R_1 having negative and R_2 positive x-values. (Fig. 5.2). Thus, the coordinates of the receivers are:

$$\begin{aligned} R_0 &: \quad (0,0,0) \\ R_1 &: \quad (x_1, 0, z_1) \\ R_2 &: \quad (x_2, 0, z_2) = (-x_1, 0, z_1) \\ R_3 &: \quad (0, 0, z_3) \end{aligned}$$

Distances between emitter and receiver 2 Inserting the positions of the receivers into the equations for the receiver-emitter-distance yields:

$$R_0: \quad d_0^2 = r = \quad x_E^2 \quad + y_E^2 + z_E^2 \tag{5.15}$$
$$R_1: \quad d_1^2 = \quad (x_E - x_1)^2 + y_E^2 + (z_E - z_1)^2 \tag{5.16}$$
$$R_2: \quad d_2^2 = \quad (x_E - x_2)^2 + y_E^2 + (z_E - z_2)^2$$
$$d_2^2 = \quad (x_E + x_1)^2 + y_E^2 + (z_E - z_1)^2 \tag{5.17}$$
$$R_3: \quad d_3^2 = \quad x_E^2 \quad + y_E^2 + (z_E - z_3)^2 \tag{5.18}$$

So now we have four quadratic equations with seven unknowns, which are the coordinates of the emitter (that's what we're after) and the four distances from the receivers to the emitter. We now have to rewrite these four distances in such a way that only one unknown remains (i.e., four equations with four unknowns), which can then be solved.

Solving the equations 1: Replacing emitter positions by r The distance between the central receiver R_0 and the emitter (Eq. 5.15) links the emitter coordinates to the radius. We can thus replace the emitter coordinates in the distance equations for the receivers R_1, R_2 and R_3 by expanding the distance equations 5.16 - 5.18:

$$\begin{aligned} R_1: \quad d_1^2 &= (x_E - x_1)^2 + y_E^2 + (z_E - z_1)^2 \\ &= x_E^2 - 2x_E x_1 + x_1^2 + y_E^2 + z_E^2 - 2z_E z_1 + z_1^2 \\ &= x_E^2 + y_E^2 + z_E^2 + x_1^2 - 2x_E x_1 + z_1^2 - 2z_E z_1 \\ d_1^2 &= r^2 + x_1^2 - 2x_E x_1 + z_1^2 - 2z_E z_1 \end{aligned} \tag{5.19}$$

$$\begin{aligned} R_2: \quad d_2^2 &= (x_E + x_1)^2 + y_E^2 + (z_E - z_1)^2 \\ &= x_E^2 + 2x_E x_1 + x_1^2 + y_E^2 + z_E^2 - 2z_E z_1 + z_1^2 \\ &= x_E^2 + y_E^2 + z_E^2 + x_1^2 + 2x_E x_1 + z_1^2 - 2z_E z_1 \\ d_2^2 &= r^2 + x_1^2 + 2x_E x_1 + z_1^2 - 2z_E z_1 \end{aligned} \tag{5.20}$$

$$\begin{aligned} R_3: \quad d_3^2 &= x_E^2 + y_E^2 + (z_E - z_3)^2 \\ &= x_E^2 + y_E^2 + z_E^2 - 2z_E z_3 + z_3^2 \\ &= x_E^2 + y_E^2 + z_E^2 + z_3^2 - 2z_E z_3 \\ d_3^2 &= r^2 + z_3^2 - 2z_E z_3 \end{aligned} \tag{5.21}$$

Solving the equations 2: Replacing emitter positions by AZ and EL We have already introduced the spherical coordinate r to replace some occurences of the Cartesian coordinates of the emitter, x_E, y_E and z_E. Now, we use the conversion of cartesian to spherical coordintes (Eq. 5.7 - 5.9) to replace all of the remaining emitter Cartesian coordinates.

$$\begin{aligned} R_1: \quad d_1^2 &= r^2 + x_1^2 - 2x_E x_1 + z_1^2 - 2z_E z_1 \\ &= r^2 + x_1^2 - 2rx_1 sinAZcosEL + z_1^2 - 2rz_1 sinEL \\ &= r^2 - 2rx_1 sinAZcosEL - 2rz_1 sinEL + x_1^2 + z_1^2 \\ d_1^2 &= r^2 - 2r(x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2 \end{aligned} \tag{5.22}$$

$$\begin{aligned}
R_2: \quad d_2^2 &= r^2 + \qquad x_1^2 + 2x_E x_1 \qquad + \quad z_1^2 - 2z_E z_1 \\
&= r^2 + \quad x_1^2 + 2rx_1 sinAZcosEL \quad + z_1^2 - 2rz_1 sinEL \\
&= r^2 + \; 2rx_1 sinAZcosEL - 2rz_1 sinEL \; + \quad x_1^2 + z_1^2 \\
d_2^2 &= r^2 - 2r(-x_1 sinAZcosEL + z_1 sinEL) + \quad x_1^2 + z_1^2
\end{aligned} \tag{5.23}$$

$$\begin{aligned}
R_3: \quad d_3^2 &= r^2 \qquad + \quad z_3^2 - 2z_E z_3 \\
&= r^2 \qquad + z_3^2 - 2rz_3 sinEL \\
d_3^2 &= r^2 - \qquad 2rz_3 sinEL \qquad + \qquad z_3^2
\end{aligned} \tag{5.24}$$

So now we have three quadratic equations with six unknowns, which are the coordinates of the emitter in spherical coordinates (that's what we're after) and the three distances from the peripheral receivers to the emitter. Let's look at the TOADs again:

Solving the equations 3: Linking squared distance to TOAD The TOAD-definitions from above (Eq. 5.4 - 5.6) link the unknown receiver-emitter distance to the measured TOADs. We now square them to get distance-squared:

$$\begin{aligned}
R_1: \quad d_1^2 &= (r - c \cdot \tau_1)^2 \\
d_1^2 &= r^2 - 2rc\tau_1 + (c\tau_1)^2
\end{aligned} \tag{5.25}$$

$$\begin{aligned}
R_2: \quad d_2^2 &= (r - c \cdot \tau_2)^2 \\
d_2^2 &= r^2 - 2rc\tau_2 + (c\tau_2)^2
\end{aligned} \tag{5.26}$$

$$\begin{aligned}
R_3: \quad d_3^2 &= (r - c \cdot \tau_3)^2 \\
d_3^2 &= r^2 - 2rc\tau_3 + (c\tau_3)^2
\end{aligned} \tag{5.27}$$

So now we go on and combine the two different sets of equations that we have for the squared distances. For each receiver separately, we will replace the squared distance with the measured TOADs. Thus, we will end up with three equations with three unknowns to solve.

Replacing distance by TOAD: Receiver R_3 From above, it is:

$$\begin{aligned}
d_3^2 &= r^2 - 2rz_3 sinEL + \quad z_3^2 && |\leftarrow \text{(5.24) above} \\
d_3^2 &= r^2 - \quad 2rc\tau_3 \quad + (c\tau_3)^2 && |\leftarrow \text{(5.27) above}
\end{aligned}$$

Equalizing these equations, we can solve for the elevation EL:

$$\begin{aligned} -2rz_3 sinEL + z_3^2 &= -2rc\tau_3 + (c\tau_3)^2 && |(5.24) = (5.27) \\ 2rz_3 sinEL &= 2rc\tau_3 - (c\tau_3)^2 + z_3^2 \\ sinEL &= \frac{2rc\tau_3 - (c\tau_3)^2 + z_3^2}{2rz_3} \\ \boxed{EL = \arcsin \frac{2rc\tau_3 - (c\tau_3)^2 + z_3^2}{2rz_3}} \end{aligned} \tag{5.28}$$

So now we can calculate the elevation based on τ_3 and the distance to the emitter (radius r). So next we have to obtain the radius.

Replacing distance by TOAD: Receiver R_1 From above, it is:

$$\begin{aligned} d_1^2 &= r^2 - 2r(x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2 && |\leftarrow (5.22) \text{ above} \\ d_1^2 &= r^2 - 2rc\tau_1 + (c\tau_1)^2 && |\leftarrow (5.25) \text{ above} \end{aligned}$$

Equalizing these equations, we obtain:

$$-2r(x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2 = -2rc\tau_1 + (c\tau_1)^2 \tag{5.29}$$

Replacing distance by TOAD: Receiver R_2 From above, it is:

$$\begin{aligned} d_2^2 &= r^2 - 2r(-x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2 && |\leftarrow (5.23) \text{ above} \\ d_2^2 &= r^2 - 2rc\tau_2 + (c\tau_2)^2 && |\leftarrow (5.26) \text{ above} \end{aligned}$$

Equalizing these equations, we obtain:

$$-2r(-x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2 = -2rc\tau_2 + (c\tau_2)^2 \tag{5.30}$$

Adding equations (delete the x_1-term) We now add the two previous equations derived from R_1 and R_2: (5.29) + (5.30)

$$-2r(x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2 = -2rc\tau_1 + (c\tau_1)^2 \tag{5.31}$$

$$-2r(-x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2 = -2rc\tau_2 + (c\tau_2)^2 \tag{5.32}$$

$$-4rz_1 sinEL + 2(x_1^2 + z_1^2) = -2rc(\tau_1 + \tau_2) + c^2(\tau_1^2 + \tau_2^2) \tag{5.33}$$

Substracting equations (delete the z_1-term) And we also substract those two two equations : (5.29) - (5.30)

$$\begin{aligned}
& -2r(x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2 \\
& -(-2r(-x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2) = \quad -2rc\tau_1 + (c\tau_1)^2 \\
& \qquad\qquad -(-2rc\tau_2 + (c\tau_2)^2)
\end{aligned}$$

$$\begin{aligned}
& -2r(x_1 sinAZcosEL + z_1 sinEL) + x_1^2 + z_1^2 \\
& -2r(x_1 sinAZcosEL - z_1 sinEL) - x_1^2 - z_1^2 = -2rc\tau_1 - (-2rc\tau_2) + (c\tau_1)^2 - (c\tau_2)^2 \\
& -4rx_1 sinAZcosEL = -2rc(\tau_1 - \tau_2) + c^2(\tau_1^2 - \tau_2^2) \qquad (5.34)
\end{aligned}$$

After adding and substracting the same equations, we now have two equations with the unknowns r and EL (eq. 5.33) and r, EL and AZ (eq. 5.34). Next, we will insert EL from eq. 5.28 to solve for r and AZ.