中国航空工业集团有限公司
AVIATION INDUSTRY CORPORATION OF CHINA, LTD.

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Progress and applications of ARI_Boom software for sonic boom prediction

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AVIC Aerodynamics Research Institute (AVIC ARI)

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Outline

- Backgrounds
- Introduction of ARI_Boom in-house code
- Effects of atmospheric turbulence
- Future work of ARI_Boom

Outline

Backgrounds

Introduction of ARI_Boom in-house code

Effects of atmospheric turbulence

Future work of ARI_Boom

1. Backgrounds

Civil aircraft plays an important role in the transportation system

Highway system

Railway system

Aircraft system

Highway system: 60 ~ 120 km/h → **Back and forth between different cities in one day**

Railway system: 120 ~ 350 km/h → **Back and forth between different provinces in one day**

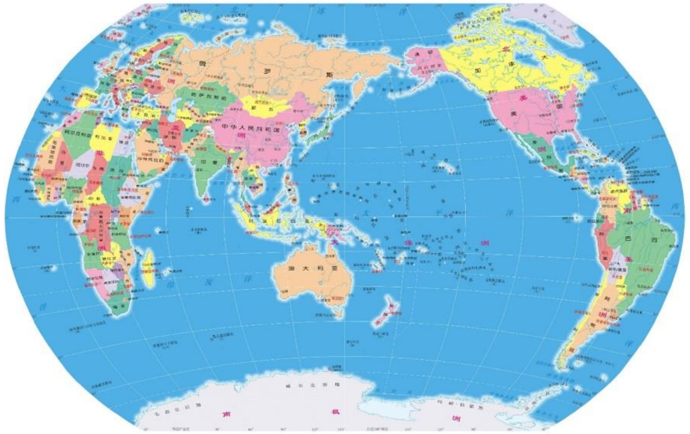
Aircraft system: 800 ~ 1000 km/h → **Back and forth between different regions in one day**

Faster travel speed is the eternal pursuit of us！

1. Backgrounds

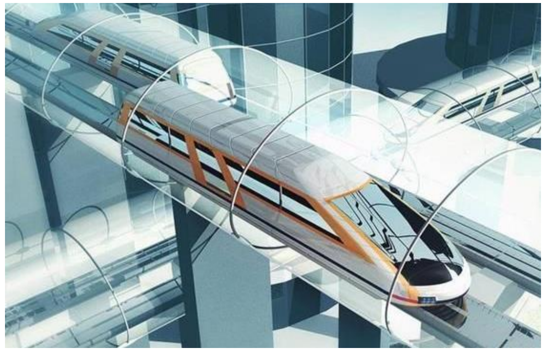
➢ Market demands for high Mach civil transport

◆ **Passengers have more demands for efficiency and comfort in air travel** **Flight time always needs be reduced！**



- Ultra-long distance travel —— Transoceanic and transcontinental
  - Travel across the Pacific and Atlantic
  - Travel across the Eurasian Continent
- Medium distance travel —— Connect major business cities
  - Travel from Tokyo/Seoul to Sanya
  - Travel from Harbin to Urumchi

◆ **High speed railway has brought a huge impact on civilian aircraft market** **More Impact is on the way！**

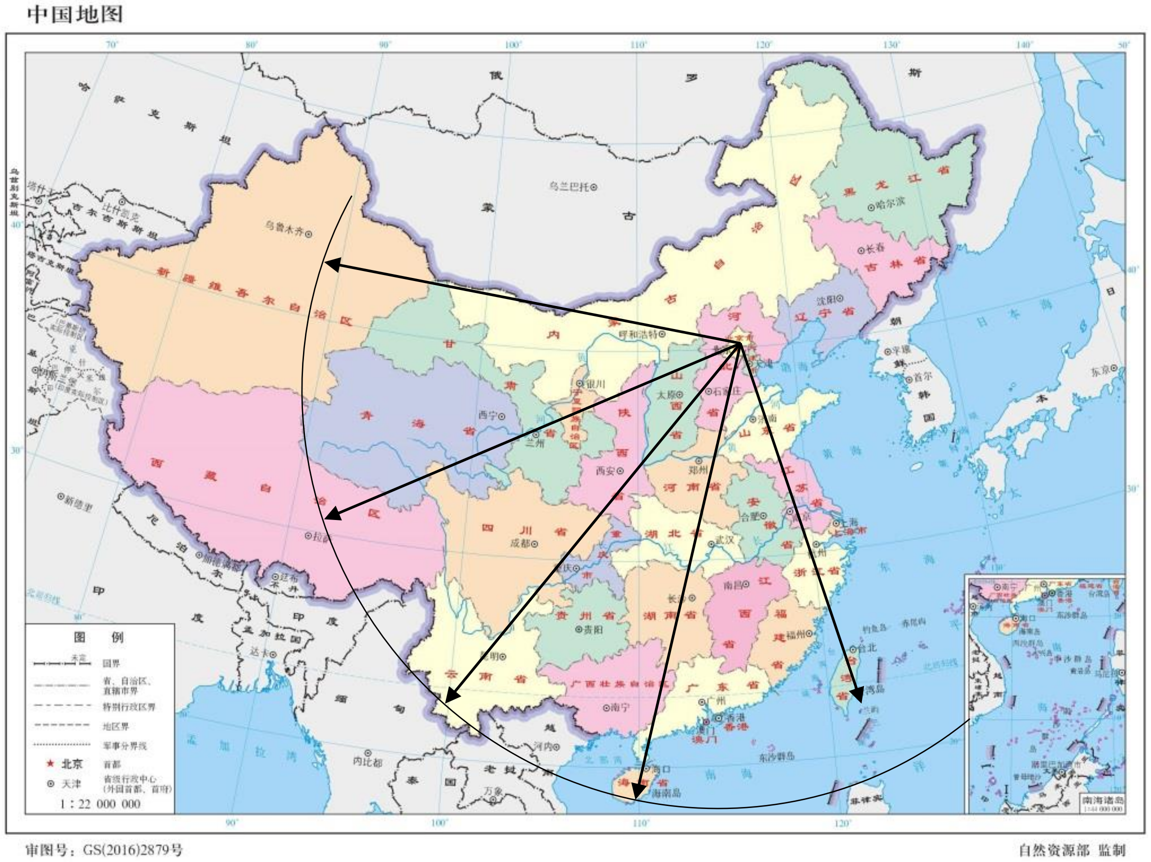


- China Fuxing Railway (CR)： 350km/h ⇨ Back and forth between different cities in one day
- New generation： 500 ~ 600km/h ⇨ Back and forth between different provinces in one day
- Hyperloop： >1000km/h ⇨ Back and forth between different regions in one day

The speed of future civil transport needs to break through sound speed

1. Backgrounds

➢ Capital 2 hours Economic Circle



Capital 2 hours Economic Circle

Present high speed train (350Km/h)

Large diameter means more infrastructure costs

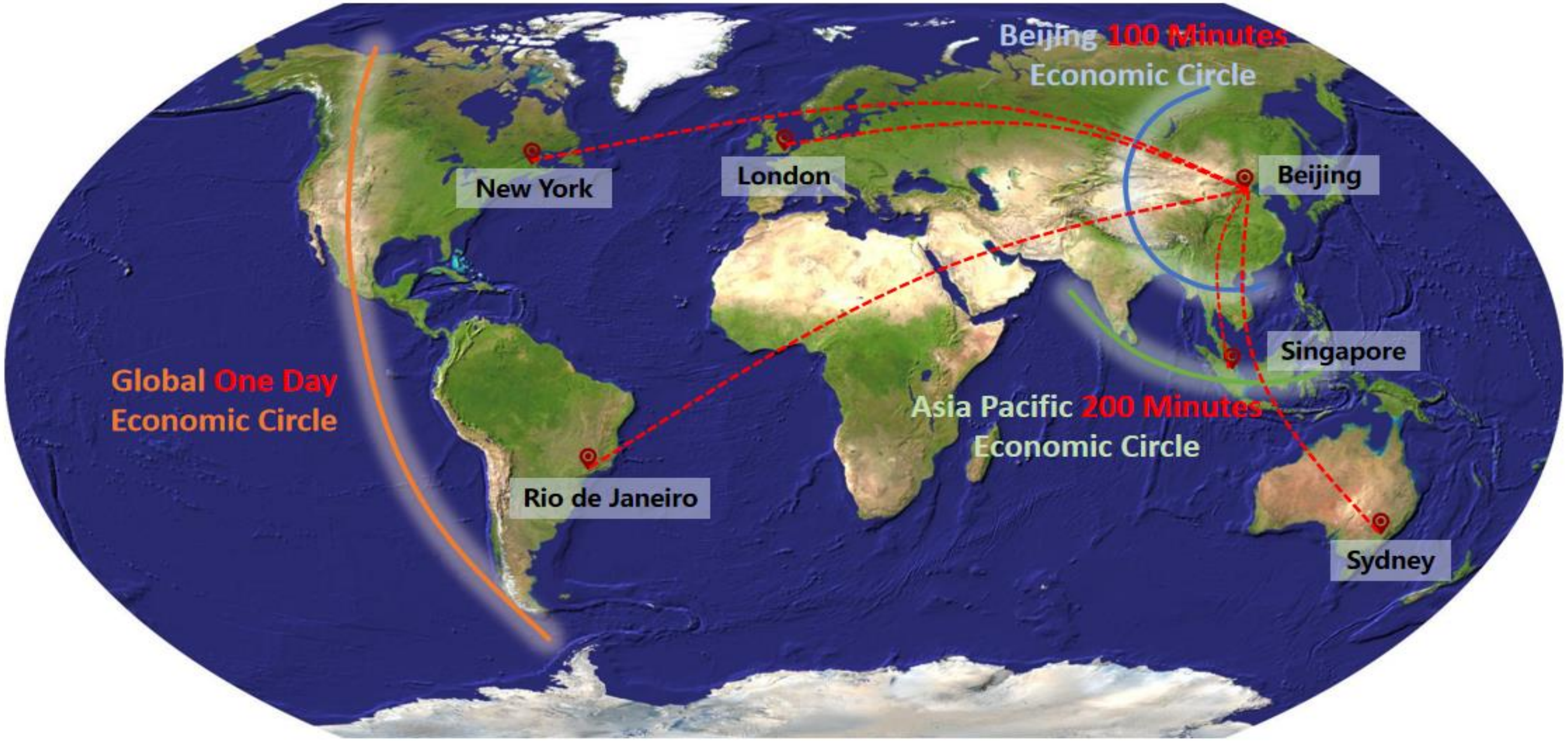
Capital 2 hours Economic Circle

Future supersonic transport

Infrastructure costs has nothing to do with distance

1. Backgrounds

➢ **Global One Day Economic Circle**



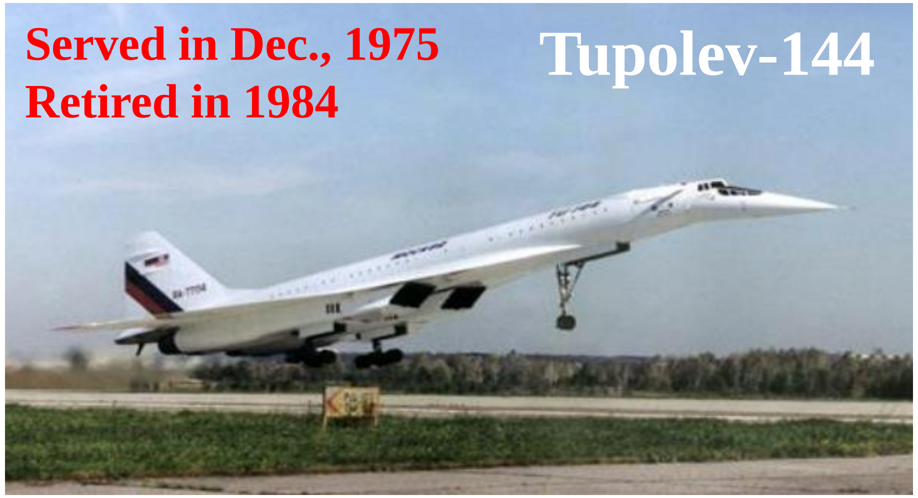
Faster | **More comfortable** | **More convenient**

Advance the Belt and Road Initiative and promote the formation of Human destiny community

1. Backgrounds

➢ **The first generation of supersonic civil aircraft**

Ma: 2.02
Rang: 6000km
Passengers: 100



Ma: 2.35
Rang: 6500km
Passengers: 140

security	economy	environment	noise
Crashworthiness Icing	Fuel efficiency	Emission	Sonic boom Airport noise

Both technical and commercial success!

1. Backgrounds

- **What will happen to the second generation ?**

In our opinion, there will be three types according to the Mach number.

- **Supersonic transport —— continuation of the first generation**
  - Cruising Mach number: $1.0<M\leq 2.5$

More realistic!

- **High supersonic transport（Sub-hypersonic speed)**
  - Cruising Mach number: $2.5<M\leq 4.5$
- **Hypersonic transport**
  - Cruising Mach number: $4.5<M$

1. Backgrounds

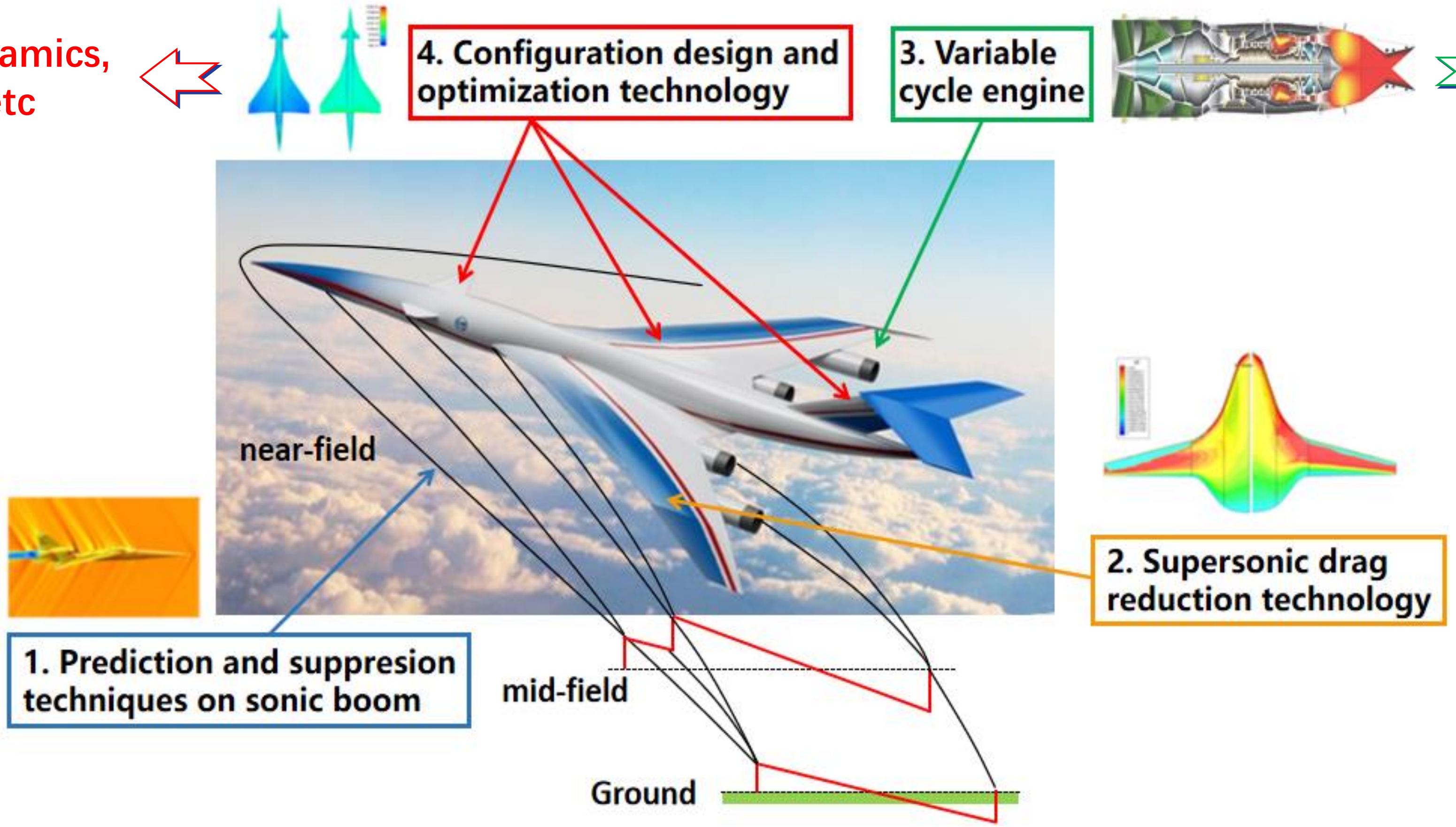
➢ **New generation of supersonic civil aircraft**

Supersonic civil aircraft is still a hot topic for international research

1. Backgrounds

➢ **Key technologies for next generation supersonic civil aircraft**

Integrated aerodynamics, structure, control, etc



Economy and reliability

Economy

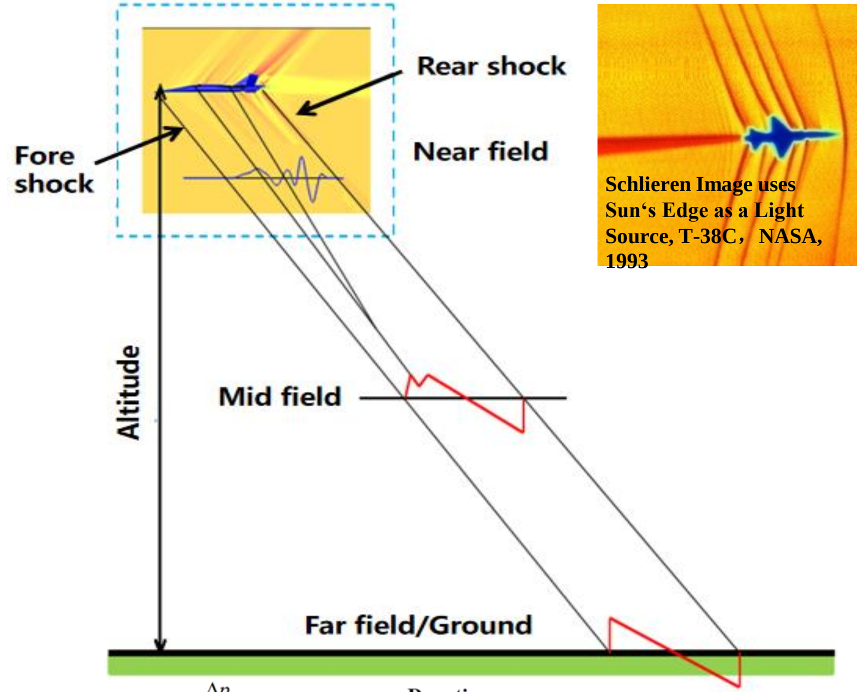
Airworthiness standard

"Green" is a main topic: Low noise, Low drag, Low emission

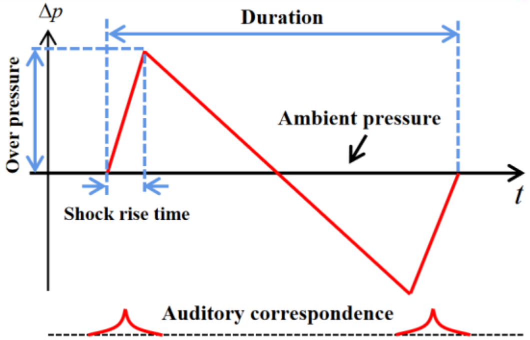
Sonic boom is one of the key obstacle in the development of supersonic civil aircraft

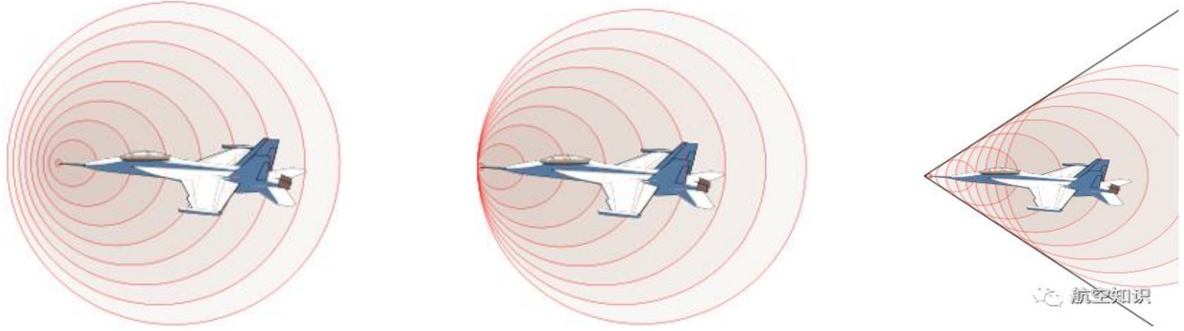
1. Backgrounds

➢ **What is the sonic boom?**



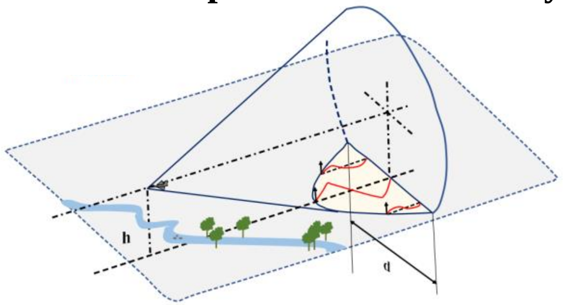
Schlieren Image uses Sun's Edge as a Light Source, T-38C, NASA, 1993

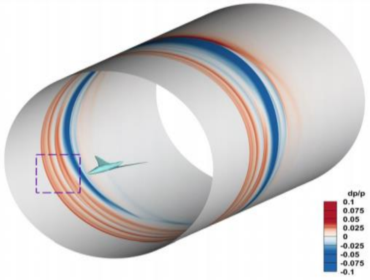


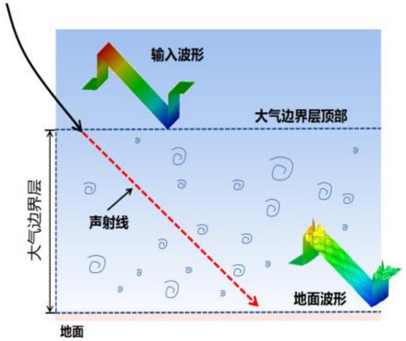


Ma<1 Ma=1 Ma>1

- **The impact of sonic boom on the ground**
  - Impact on humans and animals —— Fear
  - Impact on buildings —— Broken doors and windows
- **The sound explosion has a strong infrasound component**
  - Impact on human organs —— Resonate
  - Impact on the nervous system —— Vertigo







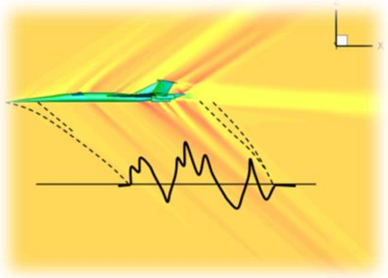
Pressure impulse: Sudden explod, Intense fluction, Wide impact range

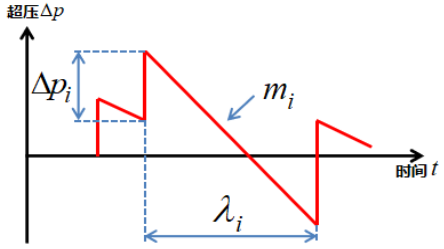
1. Backgrounds

➢ Current prediction methods of sonic boom

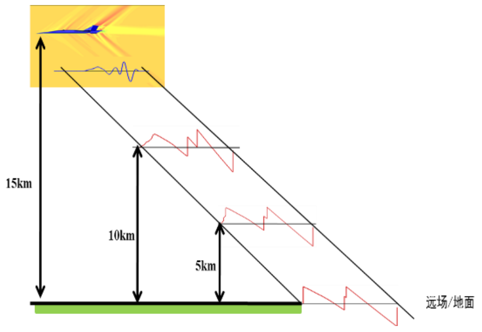
Sonic boom prediction

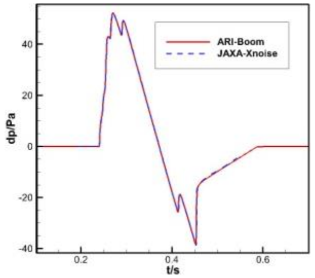
- **Rapid method**
  - Whitham theory
  - Simplified sonic boom prediction method



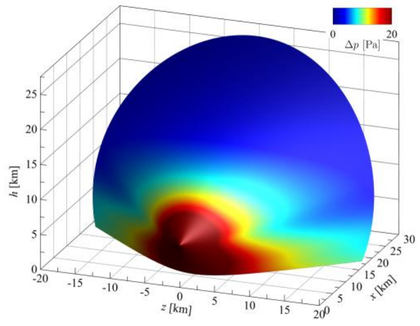


- **Hybrid method**
  - Near-field — CFD/WT
  - Far-field
    - Waveform parameter method — Linear
    - Augmented Burgers — 1D
    - KZK equation — Multi-dimensional turbulence
    - HOWARD equation — Multi-dimensional turbulence
    - Tricomi equation — Superboom





- **Full-field simulation method**



Outline

Backgrounds

Introduction of ARI_Boom in-house code

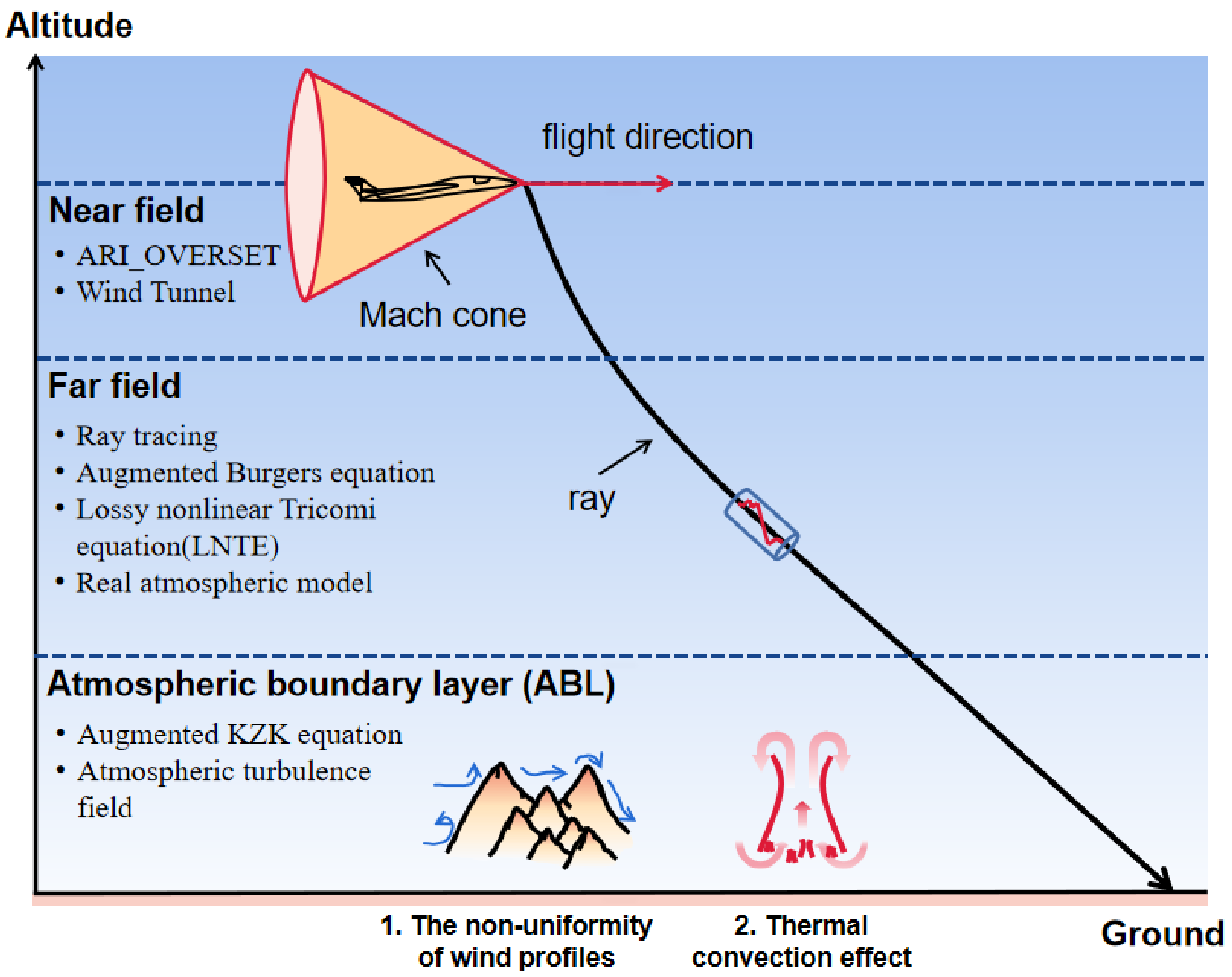
Effects of atmospheric turbulence

Future work of ARI_Boom

2. Introduction of ARI_Boom in-house code

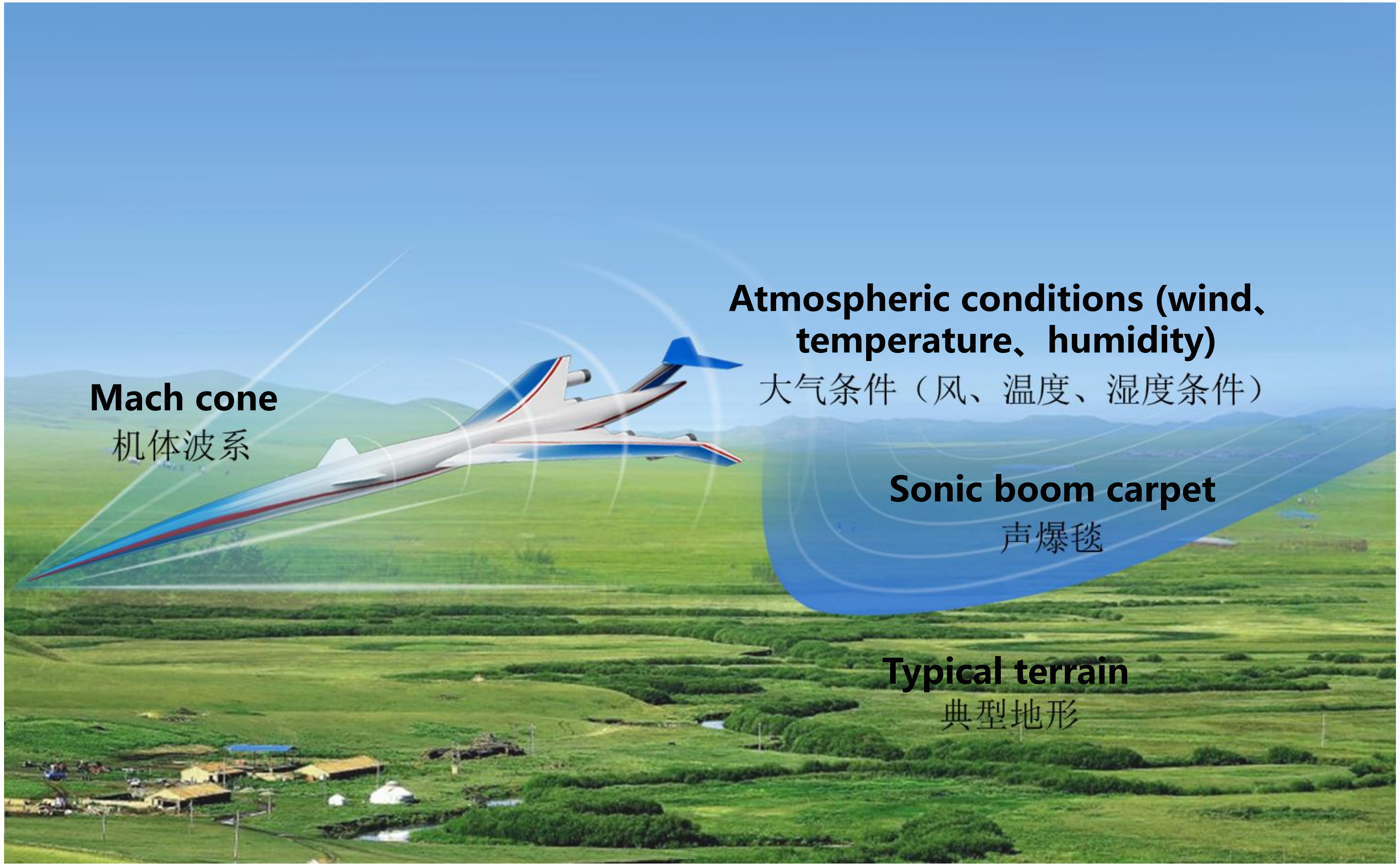
➢ Overall framework of ARI_Boom

Near-field CFD + **Far-field Propagation** = **Hybrid Method**



2. Introduction of ARI_Boom in-house code

➢ Overall framework of ARI_Boom



2. Introduction of ARI_Boom in-house code

➢ Near-field CFD numerical simulation — ARI_OVERSET

Main characteristics

- Compressible RANS solver
- 2nd order finite volume schemes
- Steady & unsteady flows

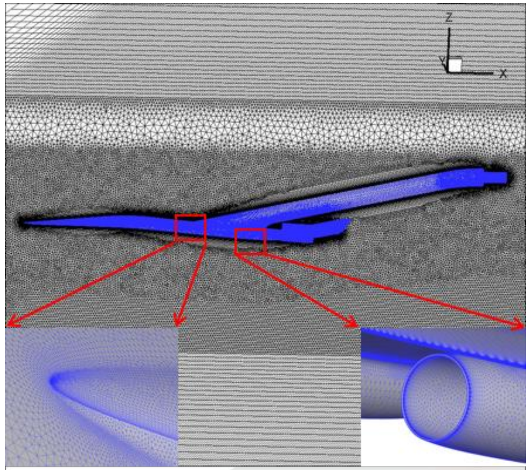
Numerical Technology

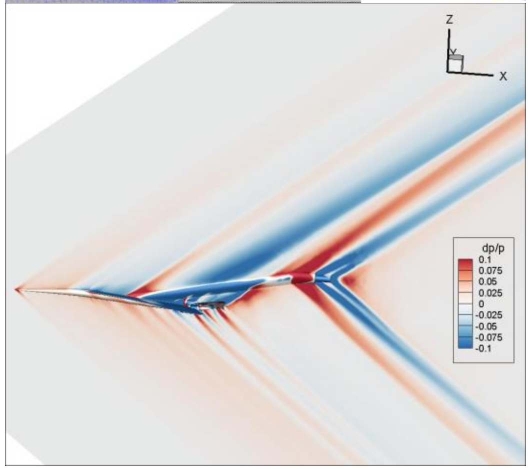
- Advanced meshes
  - ✓ Unstructured hybrid meshes
  - ✓ Dynamic overset meshes
  - ✓ Adaptive meshes
- Advanced turbulence models
  - ✓ Hybrid RANS/LES models
  - ✓ Transition models

High performance computing cluster

- 2200 Tflops capability HUAWEI
- Massively parallel computations

Model





2. Introduction of ARI_Boom in-house code

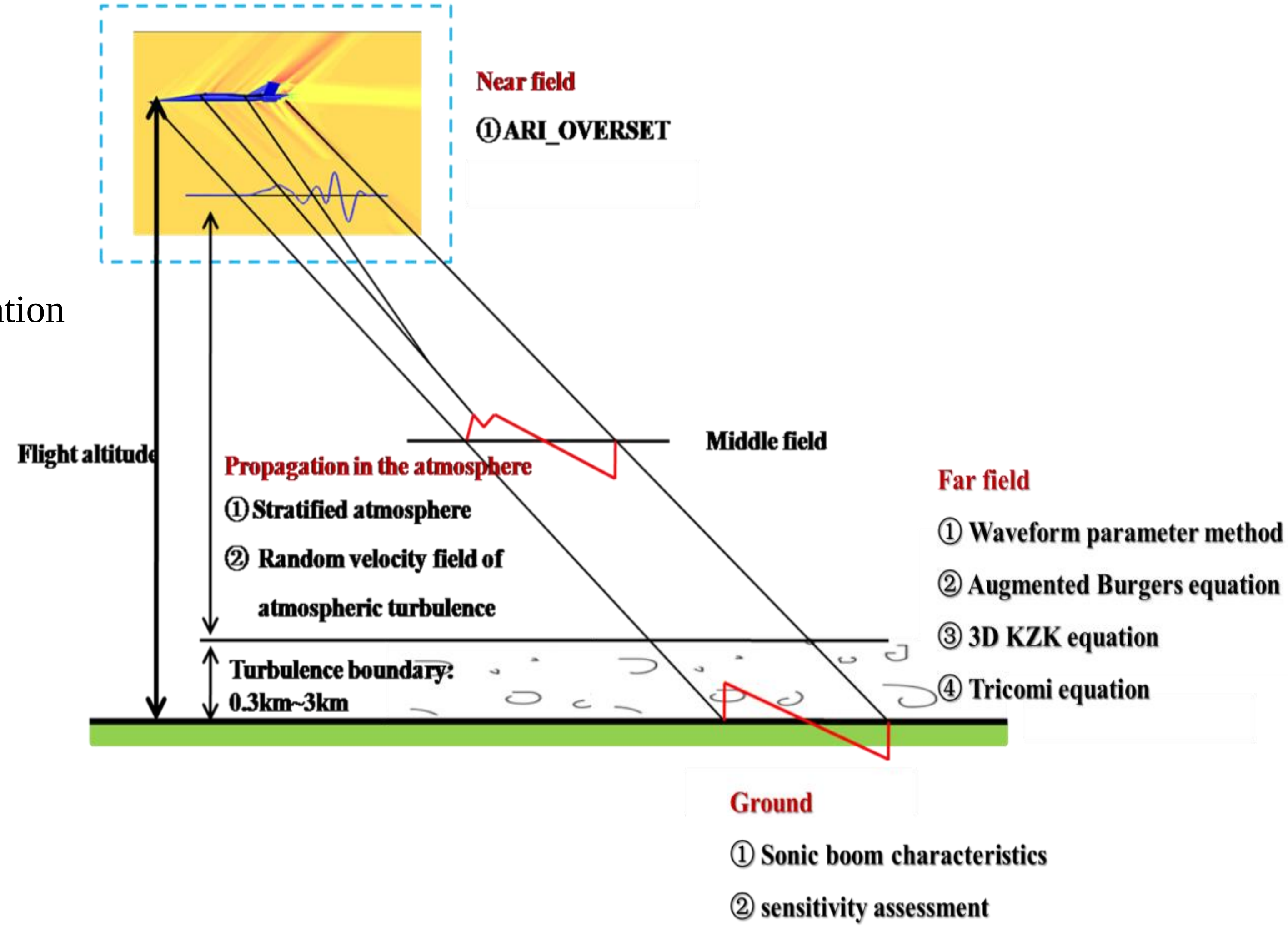
➢ Far-field propagation

Main characteristics

- **LWPE (Linear Wave Propagation Equation)**
  - ✓ Waveform Parameter Method
- **NWPE (Nonlinear Wave Propagation Equation)**
  - ✓ Augmented Burgers equation
  - ✓ Lossy nonlinear Tricomi equation (LNTE)
  - ✓ Khokhlov-Zabolotskaya-Kuznetsov (KZK) equation
- **Real atmosphere model**
  - ✓ Stratified atmosphere model
  - ✓ Wind
  - ✓ Turbulence in ABL

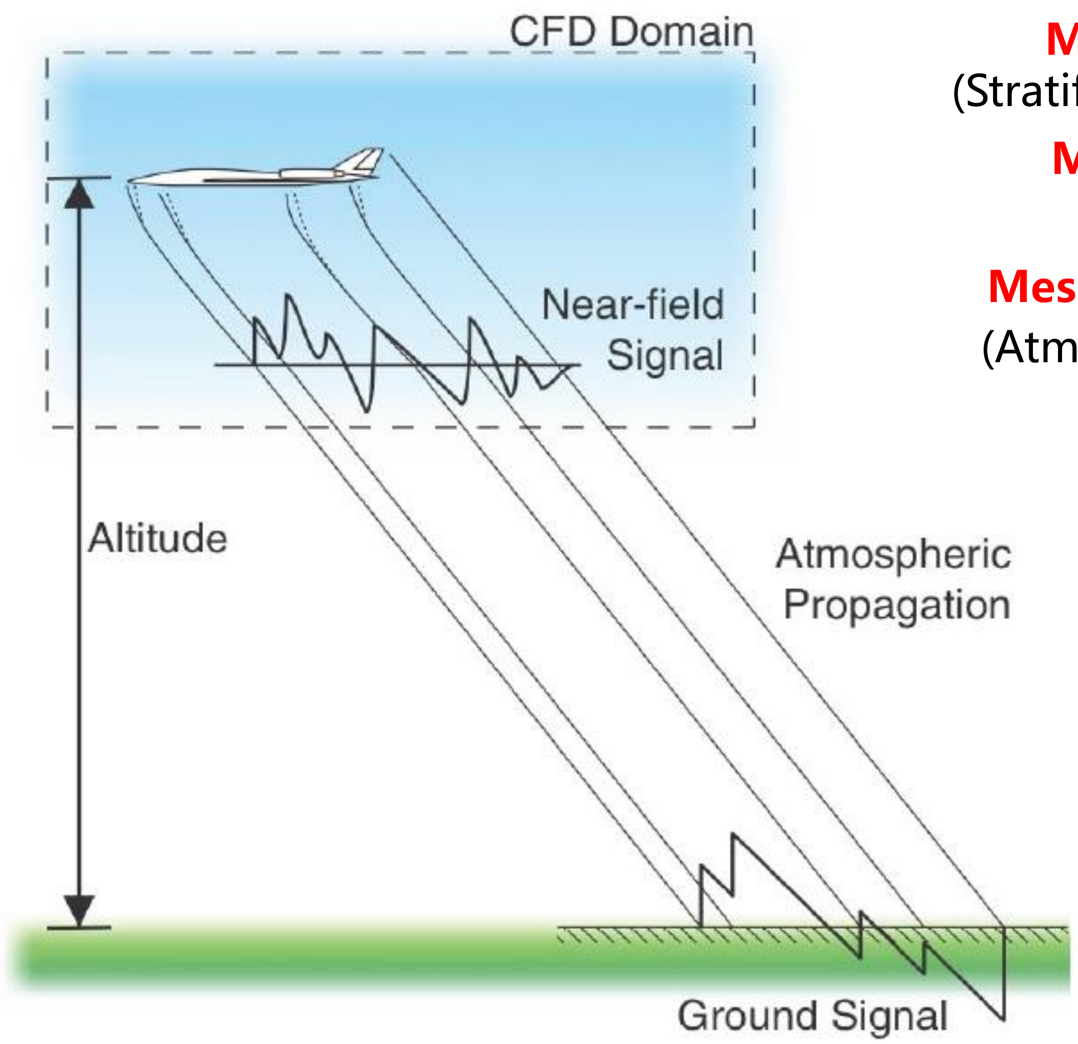
Numerical Technology

- **Thomas method**
  - ✓ Ray tracing
- **Time/frequency domain solver**
  - ✓ Fraction method
  - ✓ High order finite difference scheme



2. Introduction of ARI_Boom in-house code

➢ Atmosphere condition —— Real atmospheric environment

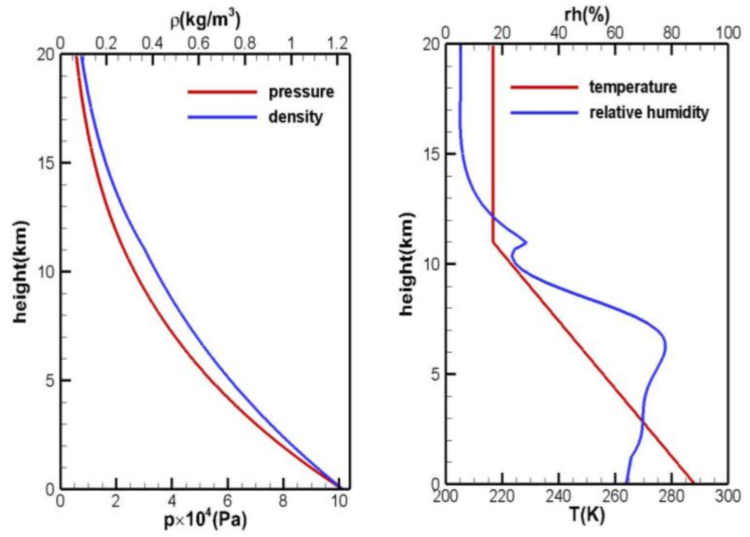


Macro scale effect
(Stratified atmosphere, wind)

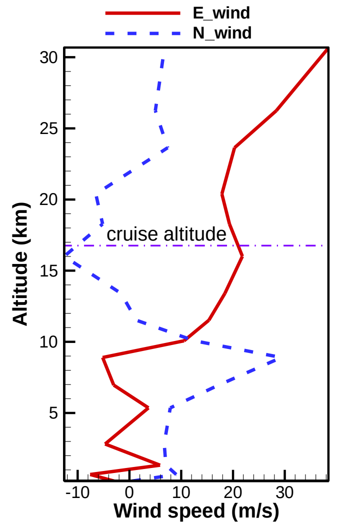
Micro scale effect
(Acoustic effect)

- ★ Molecular relaxation
- ★ Thermoviscous absorption

Mesoscopic scale effect
(Atmospheric turbulence)



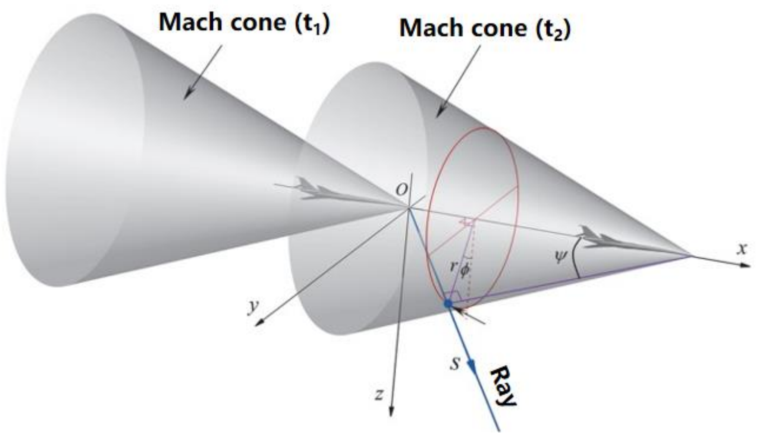
Pressure and Temperature Profile of the standard atmosphere

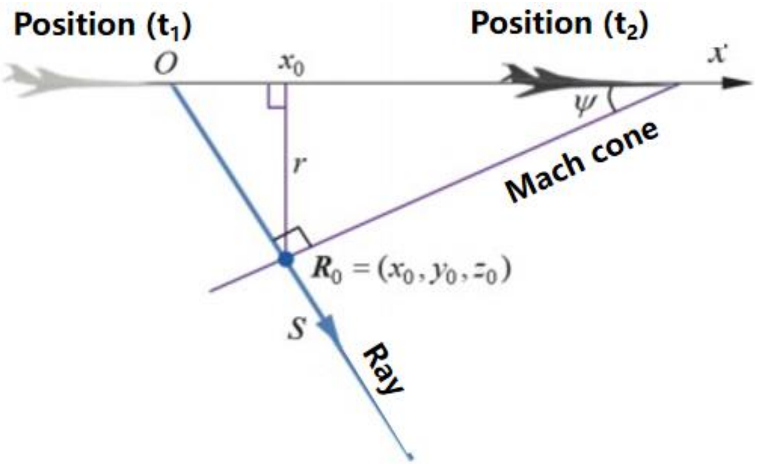


Typical wind and humidity profile

2. Introduction of ARI_Boom in-house code

➢ Ray tracing method (Geometric Acoustic Theory)

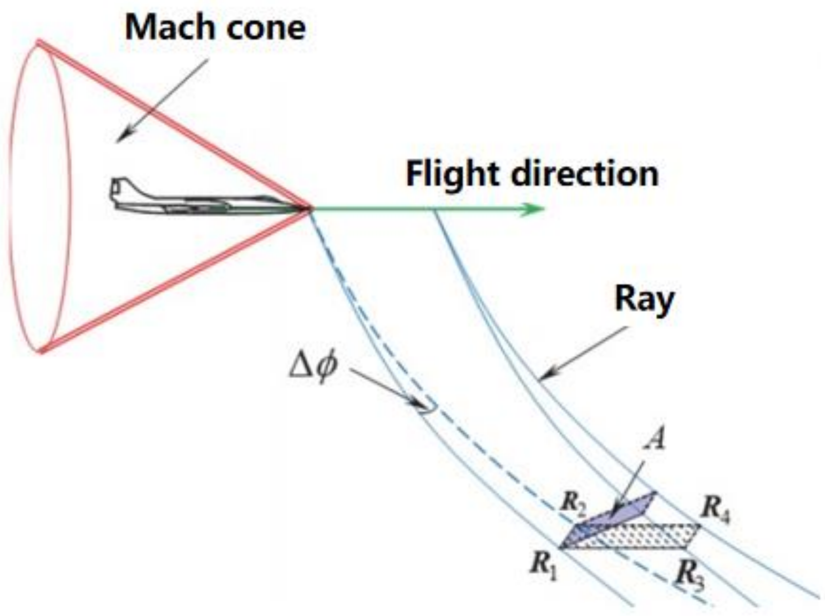




Sonic boom propagation path:

$$\begin{cases} \boldsymbol{R}(i+1) = \boldsymbol{R}(i) + \Delta\boldsymbol{R}(i) \\ \boldsymbol{N}(i+1) = \boldsymbol{N}(i) + \Delta\boldsymbol{N}(i) \end{cases}$$

$$\begin{cases} \Delta\boldsymbol{R}(i) = \left[a_0(i)\boldsymbol{N}(i) + \boldsymbol{V}_0(i)\right]\Delta t \\ \Delta\boldsymbol{N}(i) = \begin{bmatrix} DN_x(i) \\ DN_y(i) \\ DN_Z(i) \end{bmatrix} = F(i)\begin{bmatrix} N_x(i)N_z(i) \\ N_y(i)N_z(i) \\ -N_x^2(i) - N_y^2(i) \end{bmatrix} \\ F(i) = N_x(i)\dfrac{dV_{0x}}{dz}(i) + N_y(i)\dfrac{dV_{0y}}{dz}(i) + N_z(i)\dfrac{dV_{0z}}{dz}(i) + \dfrac{da_0}{dz}(i) \end{cases}$$



Area of ray tube:

$$S = \frac{1}{2}\{(\boldsymbol{R}_4 - \boldsymbol{R}_1) \times (\boldsymbol{R}_3 - R_2)\} \cdot \boldsymbol{N}_1$$

2. Introduction of ARI_Boom in-house code

➢ NWPE —— Thomas waveform parameter Method[1]

The characteristics of sonic boom are controlled by 3 parameters:

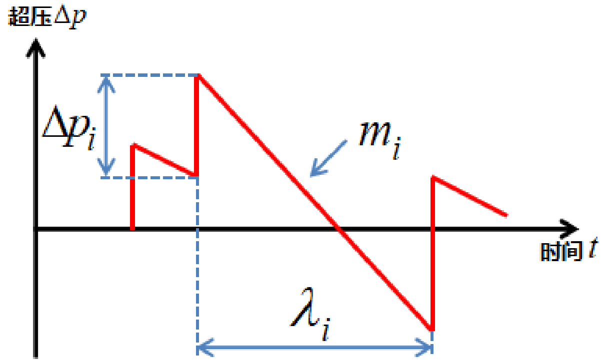
$$
\begin{cases}
\dfrac{dm_i}{dt} = C_1 m_i^2 + C_2 m_i \\
\dfrac{d\Delta p_i}{dt} = \dfrac{1}{2} C_1 \Delta p_i \left(m_i + m_{i-1} \right) + C_2 \Delta p_i \\
\dfrac{d\lambda_i}{dt} = -\dfrac{1}{2} C_1 \left(\Delta p_i + \Delta p_{i+1} \right) - C_1 m_i \lambda_i
\end{cases}
$$

where,

$$c_1 = \frac{1}{2}\left(\frac{3}{a_0}\frac{da_0}{dt} + \frac{1}{\rho_0}\frac{d\rho_0}{dt} - \frac{4}{c_n}\frac{dc_n}{dt} - \frac{1}{A}\frac{dA}{dt} \right)$$

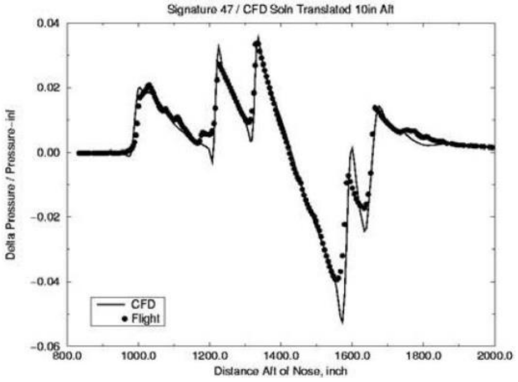
$$c_2 = c_1 + \frac{1}{c_n}\frac{dc_n}{dt} \qquad c_3 = \frac{1}{c_n}\frac{dc_n}{dt}$$

$$k = \frac{\gamma+1}{2\gamma}\frac{a_0}{p_0}$$

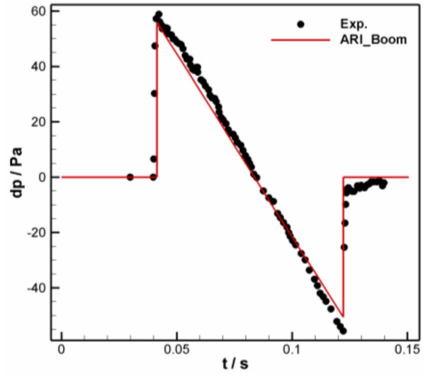


Cases —— F-5E flilght test

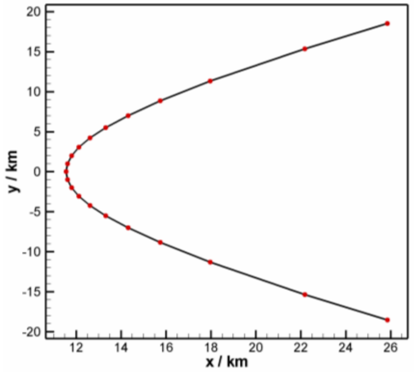
- ➢ Length： 14.3 meters
- ➢ Ma number： 1.4
- ➢ Cruise altitude： 9753.6 meters
- ➢ R/L： 2
- ➢ Ground reflection factor： 1.9



Near-field signals



Comparison of measured and predicted waveforms on the ground



Sonic boom carpet

- ☐ The overpressure is larger than the actual data;
- ☐ Unable to calculate the rise time of the sonic boom.

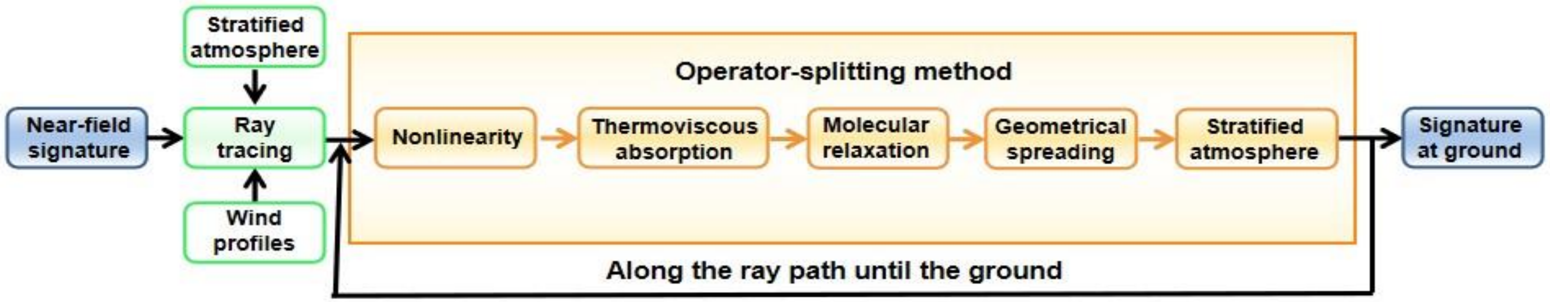
[1] Thomas C L. Extrapolation of sonic boom pressure signatures by the waveform parameter method. NASA TN D-6832, 1972.

2. Introduction of ARI_Boom in-house code

➢ NWPE —— Augmented Burgers equation[1]

$$\frac{\partial P}{\partial \sigma} = P\frac{\partial P}{\partial \tau} + \frac{1}{\Gamma}\frac{\partial^2 P}{\partial \tau^2} + \sum_{\upsilon} C_{\upsilon} \frac{\frac{\partial^2}{\partial \tau^2}}{1+\theta_{\upsilon}\frac{\partial}{\partial \tau}} P - \frac{\frac{\partial}{\partial \sigma} S}{2S} P + \frac{\frac{\partial}{\partial \sigma}(\rho_0 c_0)}{2\rho_0 c_0} P$$

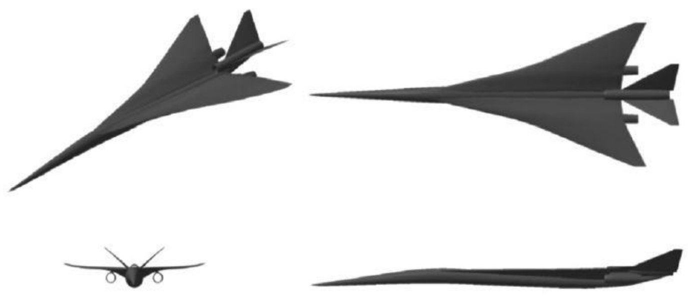
Nonlinear term	Thermoviscous absorption term	Molecular relaxation term	Geometrical spreading term	Stratified atmosphere term
5^{th} WENO	4^{th} Pade	2^{nd} Crank-Nicolson	Analyzed solution	Analyzed solution



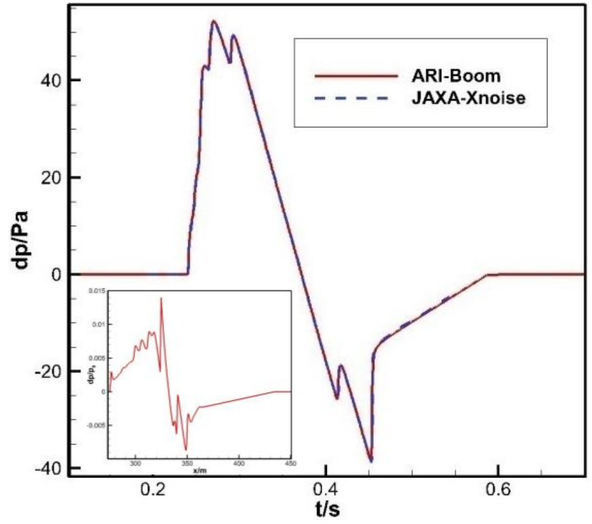
Framework of "ARI_Boom" code to solve augmented Burgers equation using the operator-splitting method

[1] CLEVELAND R O. Propagation of sonic booms through a real, stratified atmosphere[D]. Austin: The University of Texas at Austin, 1995.
[2] WANG D, QIAN Z S, LENG Y. High order scheme discretization of the sonic boom propagation model based on augmented Burgers equation. Acta Aeronautica et Astronautica Sinica, 2022, 43(01) : 289-301.

Cases



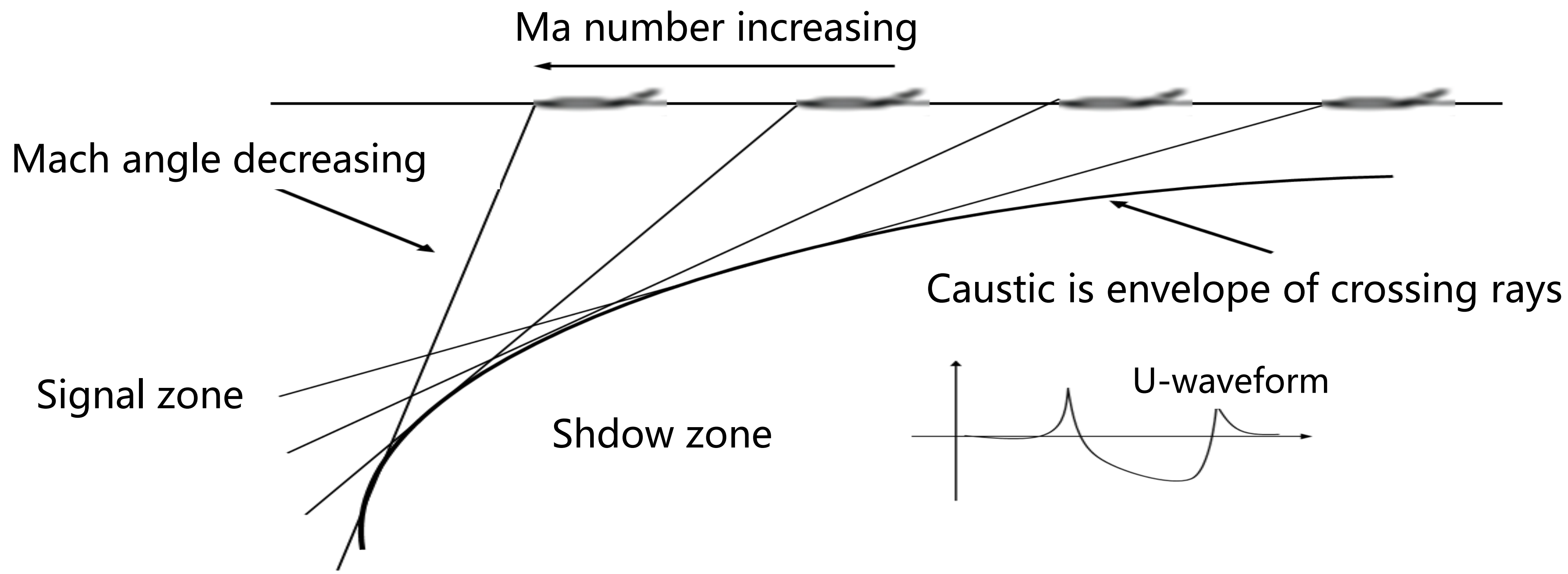
The 2nd AIAA sonic boom prediction workshop - LM1021 configuration

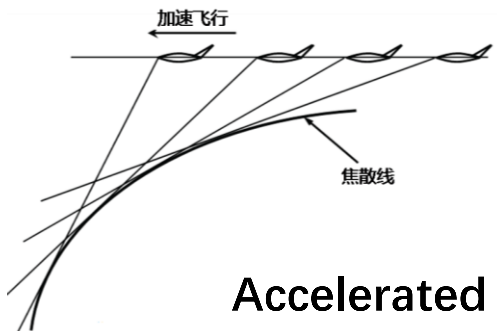


Comparison of calculation results with JAXA

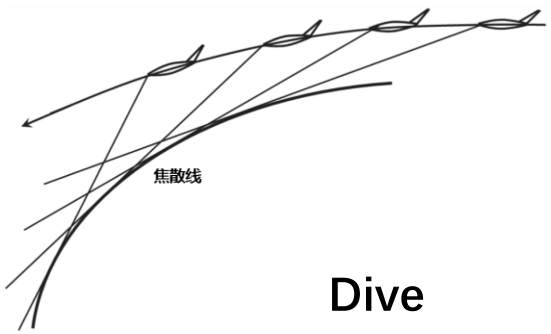
2. Introduction of ARI_Boom in-house code

➢ Supersonic maneuver (Acceleration)

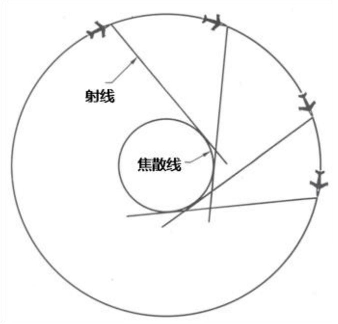




Accelerated flight



Dive



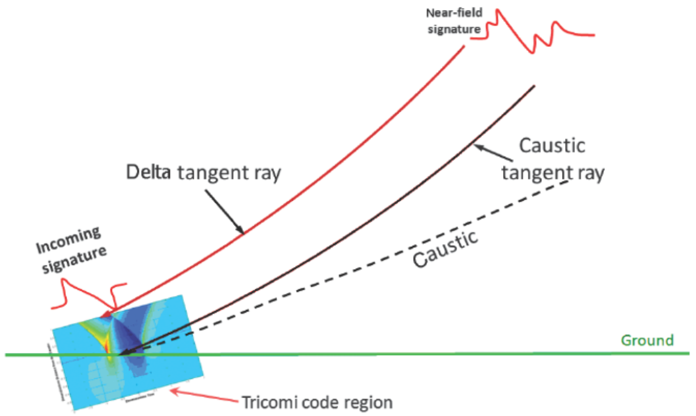
Circle

2. Introduction of ARI_Boom in-house code

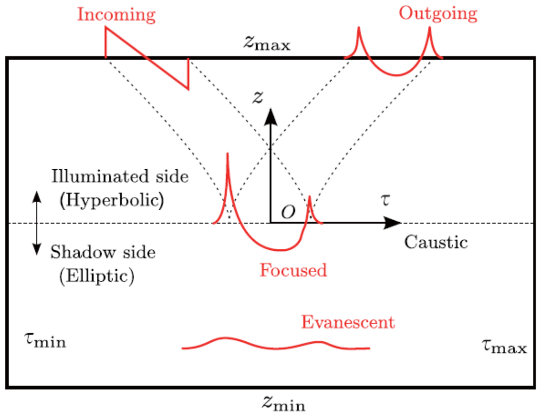
➢ NWPE —— Lossy Nonlinear Tricomi equation[1] (LNTE)

$$\frac{\partial^2 \bar{p}}{\partial \bar{z}^2} - \bar{z}\frac{\partial^2 \bar{p}}{\partial \bar{t}^2} + \frac{2M_x - M_x^2}{\varepsilon^2}\frac{\partial^2 \bar{p}}{\partial \bar{t}^2} - \frac{2M_z}{\varepsilon}\frac{\partial^2 \bar{p}}{\partial \bar{t}\partial \bar{z}} + \frac{\beta P_{ac}}{\varepsilon^2 \rho_0 c_0^2}\frac{\partial^2 \bar{p}^2}{\partial \bar{t}^2} + \left(\frac{\bar{\alpha}}{\varepsilon^2} + \sum_{\nu}\frac{\bar{\theta}_\nu/\varepsilon^2}{1+\bar{\tau}_\nu \, \partial/\partial \bar{t}}\right)\frac{\partial^3 \bar{p}}{\partial \bar{t}^3} = 0$$

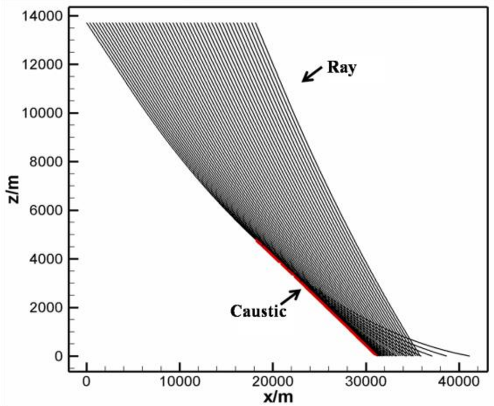
linear term diffraction	linear term wind	nonlinearity	dissipative thermoviscous absorption and molecular relaxation effects



The overview of focus boom[2]



Waves and signatures near the caustic



Rays and caustic by ARI_Boom code

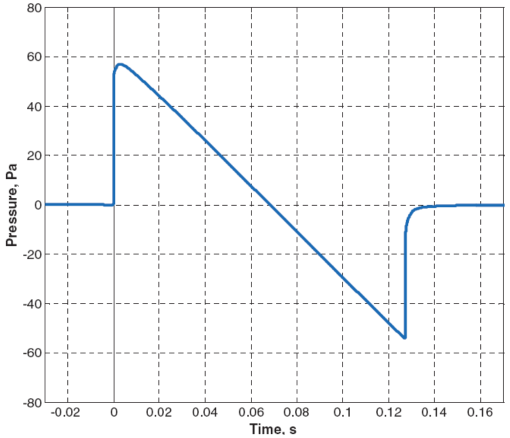
[1] Salamone, J A., Sparrow, V W, and Plotkin, K J. Solution of the Lossy Nonlinear Tricomi Equation Applied to Sonic Boom FocusingAIAA Journal, 51(7): 1745–1754, 2013.
[2] Salamone, J A , Sparrow, V W. SCAMP: Solution of the Lossy Nonlinear Tricomi Equation for Sonic Boom Focusing, AIAA paper 2013-0935, 2013.
[3] Leng Y , Zhang J B , Qian Z S . Superboom simulation for vehicles at supersonic maneuvering flight[J]. Acta Aerodynamica Sinica, 2023, 41(06): 45-54.

2. Introduction of ARI_Boom in-house code

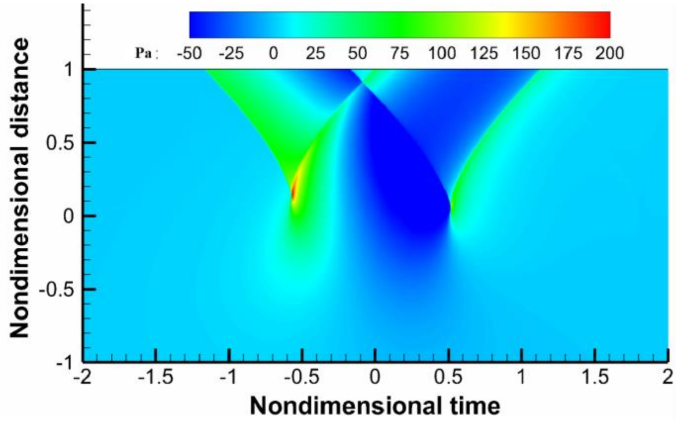
➢ NWPE —— Lossy Nonlinear Tricomi equation (LNTE)

SCAMP flight test[1]

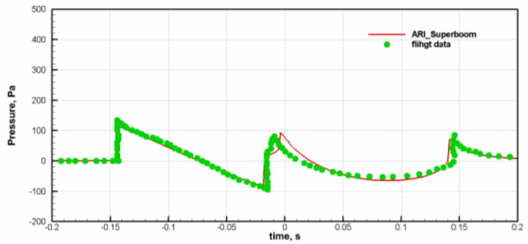
- Length: 46.3 meters
- Ma number: 1.23
- Cruise altitude: 12.8 km
- Mach rate: 0.0035/s
- Attack angle: 2.3°
- R/L: 3



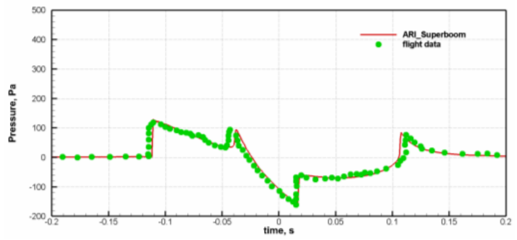
Incoming N-wave



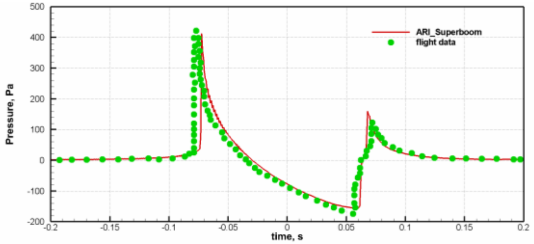
Pressure distribution by numerical simulation



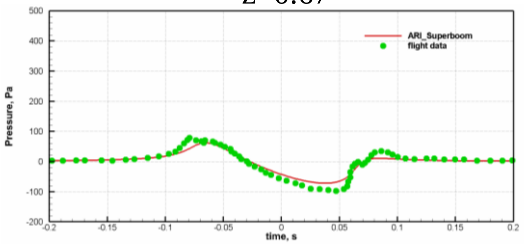
z̅=0.97



z̅=0.67



z̅=0.15



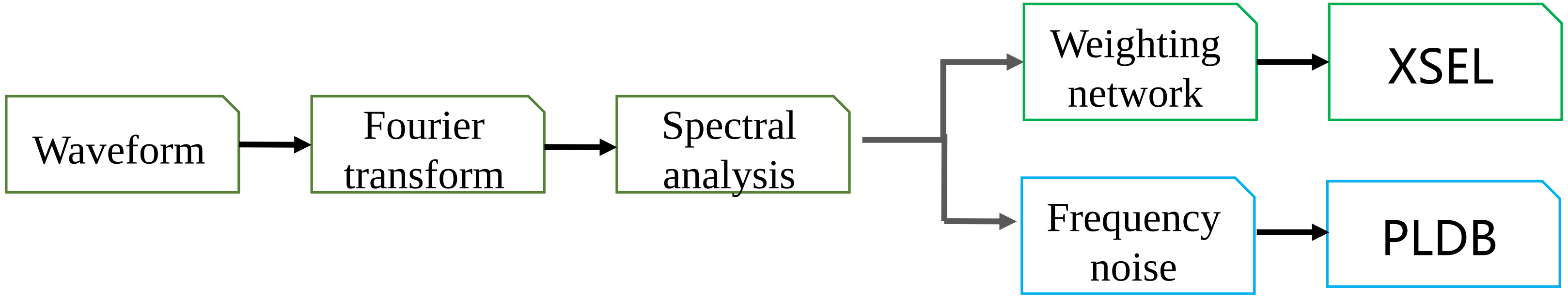
z̅=-0.22

Comparison between flight test data and numerical solutions

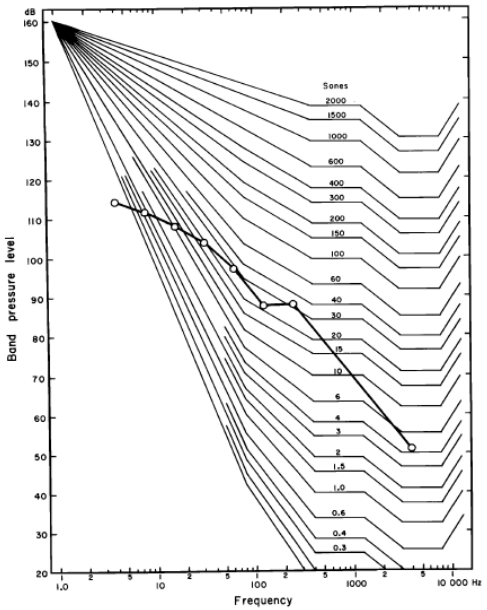
[1] Salamone, J A., Sparrow, V W, and Plotkin, K J. Solution of the Lossy Nonlinear Tricomi Equation Applied to Sonic Boom Focusing. AIAA Journal, 51(7): 1745–1754, 2013.
[2] Leng Y , Zhang J B , Qian Z S . Superboom simulation for vehicles at supersonic maneuvering flight. Acta Aerodynamica Sinica, 2023, 41(06): 45-54.

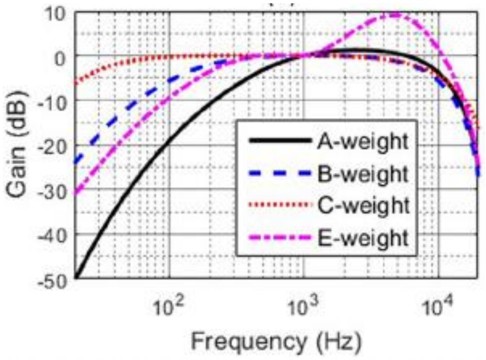
2. Introduction of ARI_Boom in-house code

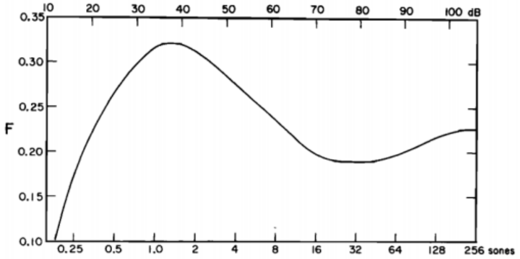
➢ Sensitivity assessment[1]



Sonic boom metrics







$$XSEL = 10\lg\left(\frac{2}{t_{\mathrm{ref}}}\frac{\int_0^{\infty}\left|\bar{p}(f)W_X(f)\right|^2 \mathrm{d}f}{p_{\mathrm{ref}}^2}\right)$$

$$S_t = S_m + F_{\mathrm{m,max}}\left(\sum S_i - S_m\right)$$

$$\mathrm{PLdB} = 32 + 9\log_2 S_t$$

PLdB is a widely used metrics!

[1] Stevens S S. Perceiced level of noise by Mark Ⅶ and decibels (E). The Journal of the Acoustical Society of America, 1972.

Outline

Backgrounds

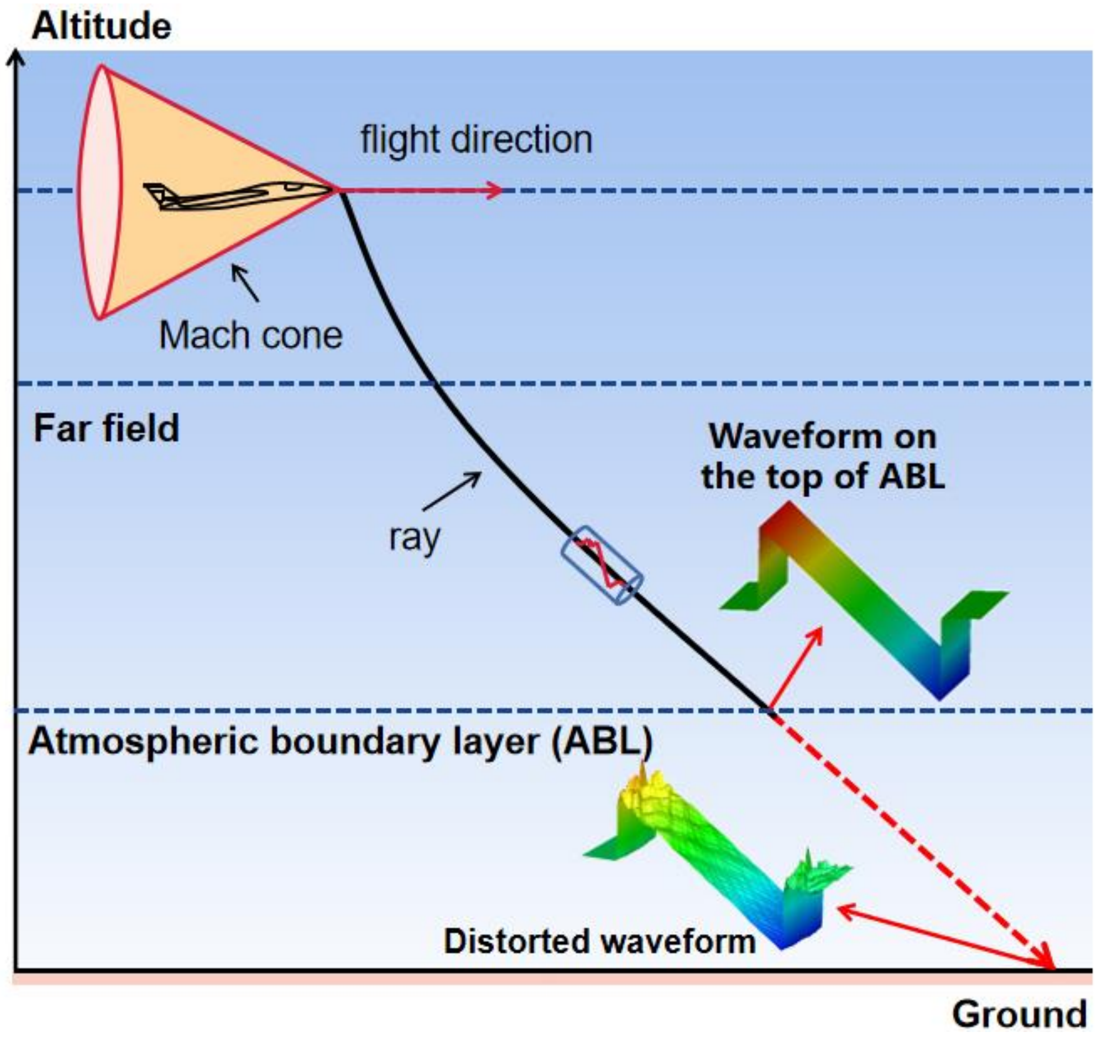
Introduction of ARI_Boom in-house code

Effects of atmospheric turbulence

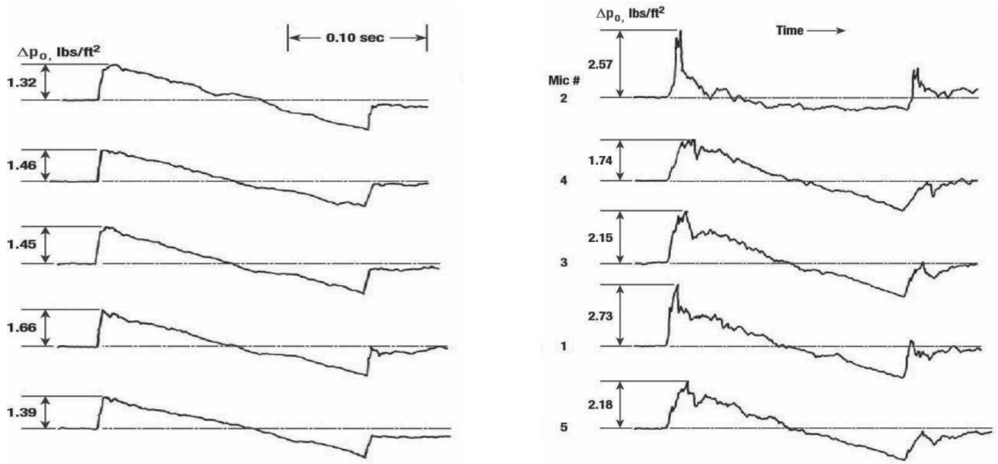
Future work of ARI_Boom

3. Effects of atmospheric turbulence

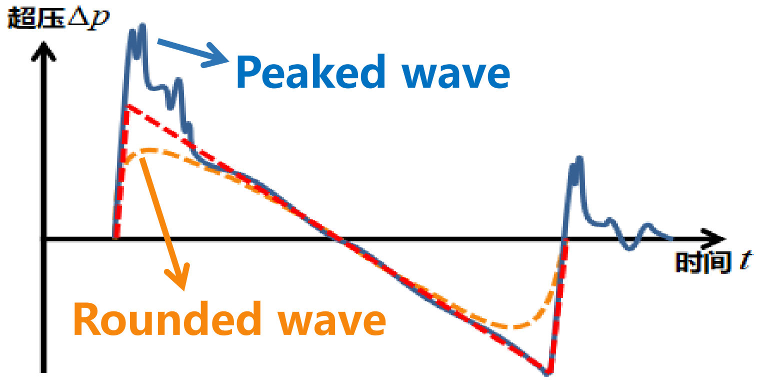
➢ Phenomenon of atmospheric turbulence



NASA flight test[1]



(a) Low disturbance (b) Strong disturbance

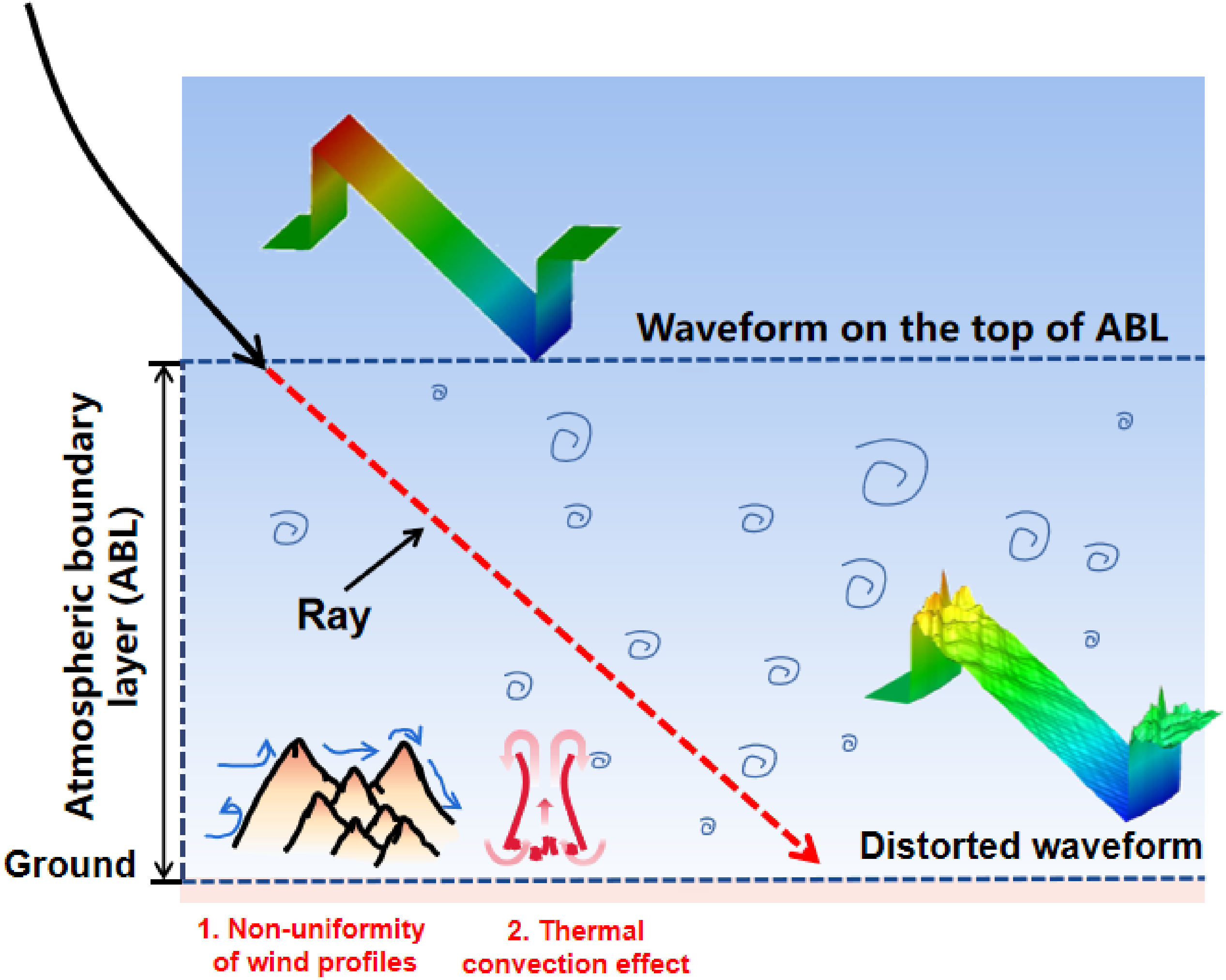


Typical characteristics of sonic boom distortion

[1] HILTON D A, HUCKEL V, MAGLIERI D J. Sonic boom measurements during bomber training operations in the Chicago area[R]. NASA TN-3655, 1966.

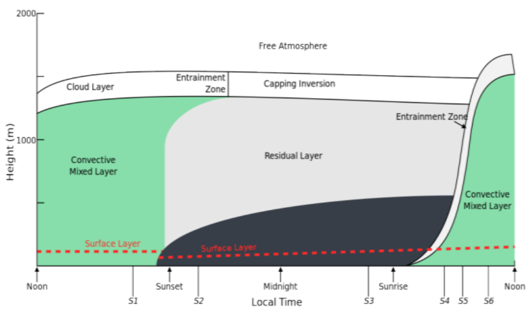
3. Effects of atmospheric turbulence

➢ Atmospheric turbulent field

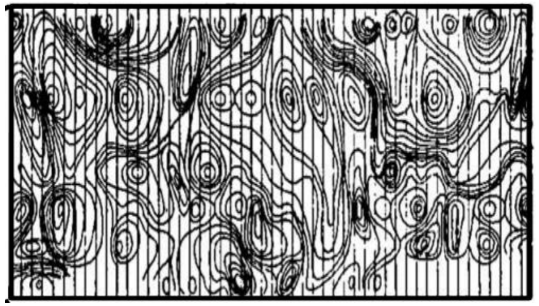


- **Non-uniformity of wind profiles**
  - Terrain（mountains、city buldings… …)
- **Thermal convection effect**
  - Surface warming
  - Ground surface（desert、ocean… …)

  (The temperature difference between day and night leads to different turbulence intensities at different time periods)
- **Climate/Weather**
- **… …**



Daily changes in ABL



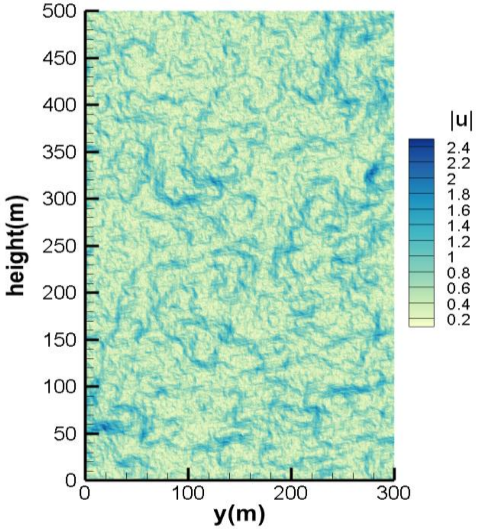
Isoline diagram of near ground vortex structure

Mainly considering the **wind** and **temperature** fluctuation

3. Effects of atmospheric turbulence

➢ Atmospheric turbulent field

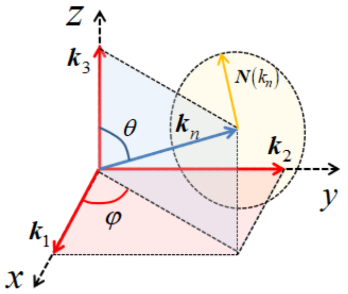
Wind fluctuation



- ✓ Altitude of ABL: 500m
- ✓ Transverse distance: 300m
- ✓ spacing: 0.5m
- ✓ Inner turbulence scale: 0.001m
- ✓ Outer turbulence scale: 40m
- ✓ Fourier number: 300
- ✓ Variance of the velocity of the fluctuated wind: 1.0 m/s

Wind fluctuation:

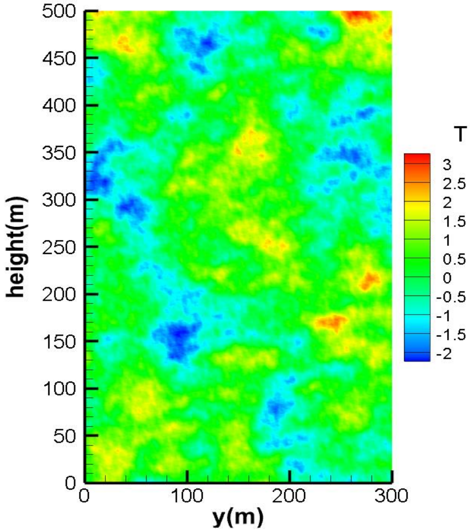
$$\begin{cases} \boldsymbol{u}(\boldsymbol{r}) = 2\sum_{n=1}^{M}\sqrt{E(k_n)\Delta k_n}\cos(\boldsymbol{k}_n\cdot\boldsymbol{r}+\varphi_n)\cdot\boldsymbol{N}(k_n) \\ \boldsymbol{N}(k_n)\cdot\boldsymbol{k}_n = 0 \end{cases}$$



Von Karman energy spectrum:

$$E(k_n) = \frac{2\sigma_u^2}{3\sqrt{\pi}L_0^{2/3}}\frac{G(17/6)}{G(1/3)}\frac{k_n^4}{\left(k_n^2+1/L_0^2\right)^{17/6}}\exp\left(-\frac{k_n^2}{k_m^2}\right)$$

Temperature fluctuation



- ✓ Altitude of ABL: 500m
- ✓ Transverse distance: 300m
- ✓ spacing: 0.5m
- ✓ Inner turbulence scale: 0.001m
- ✓ Outer turbulence scale: 40m
- ✓ Fourier number: 300
- ✓ Variance of the fluctuated temperature: 1.0 K

Temperature fluctuation:

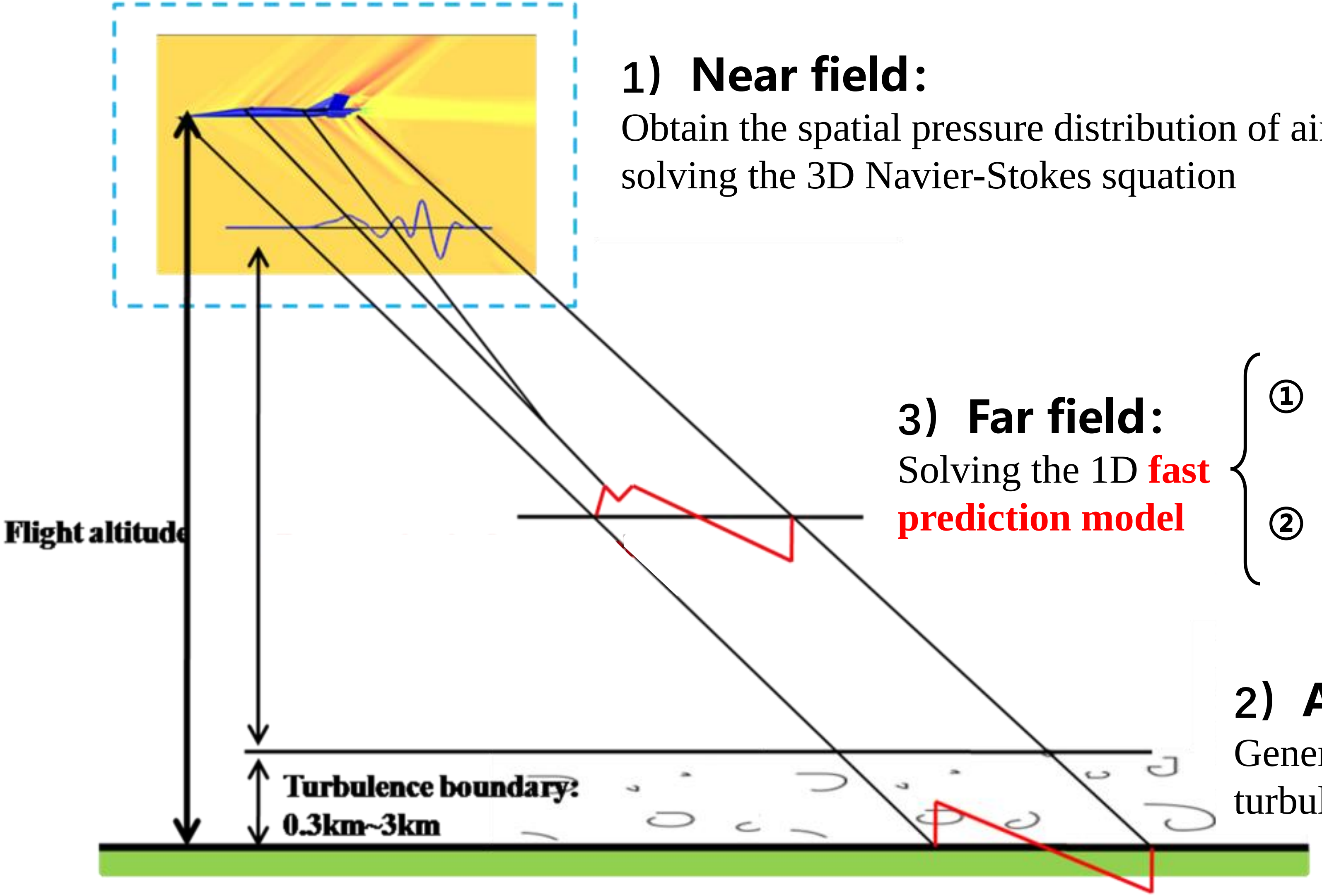
$$\boldsymbol{T}'(\boldsymbol{r}) = \sum_{n=1}^{M}\sqrt{G(k_n)\Delta k_n}\cos(\boldsymbol{k}_n\cdot\boldsymbol{r}+\varphi_n)$$

where,

$$G(k_n) = \frac{2\sigma_{T'}^2L_0^{-5/3}}{\psi\left(1,\frac{1}{6},\frac{1}{k_m^2L_0^2}\right)}\frac{k_n}{\left(k_n^2+1/L_0^2\right)^{11/6}}\exp\left(-\frac{k_n^2}{k_m^2}\right)$$

3. Effects of atmospheric turbulence

➢ 1D fast prediction method with high efficiency



1）Near field：

Obtain the spatial pressure distribution of aircraft by solving the 3D Navier-Stokes squation

3）Far field：

Solving the 1D **fast prediction model**

① **Thomas waveform parameter Method**

② **Augmented Burgers equation**

2）Atmospheric boundary layer：

Generate a random isotropic wind speed turbulence field

3. Effects of atmospheric turbulence

➢ 1D fast prediction method with low reliability

Adding the effects of **homogenous** atmospheric turbulence to the popular ray tracing method is more **convenient** and **feasible**, even just **partial effects** can be considered

The ray tracing
$$\begin{cases} R(i+1)=R(i)+\Delta R(i) \\ N(i+1)=N(i)+\Delta N(i) \end{cases}$$

⇒

$$\begin{cases} \Delta R(i)=\left[\alpha_0(i)N(i)+V_0(i)\right]\Delta t \\ \Delta N(i)=\begin{bmatrix}\Delta N_x(i)\\ \Delta N_y(i)\\ \Delta N_z(i)\end{bmatrix}=F(i)\begin{bmatrix}N_x(i)N_z(i)\\ N_y(i)N_z(i)\\ -N_x^2(i)-N_y^2(i)\end{bmatrix}\Delta t \\ F(i)=N_x(i)\frac{dV_{0x}}{dz}(i)+N_y(i)\frac{dV_{0y}}{dz}(i)+N_z(i)\frac{dV_{0z}}{dz}(i)+\frac{d\alpha_0}{dz}(i) \end{cases}$$

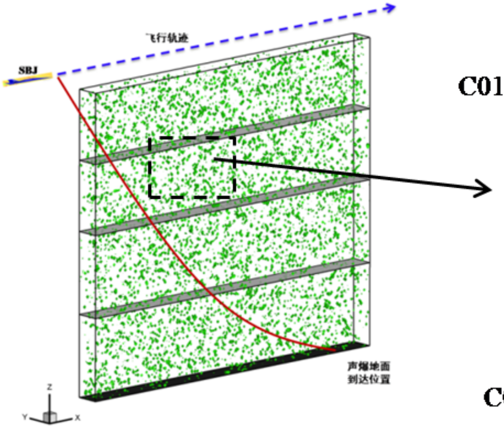
⇒

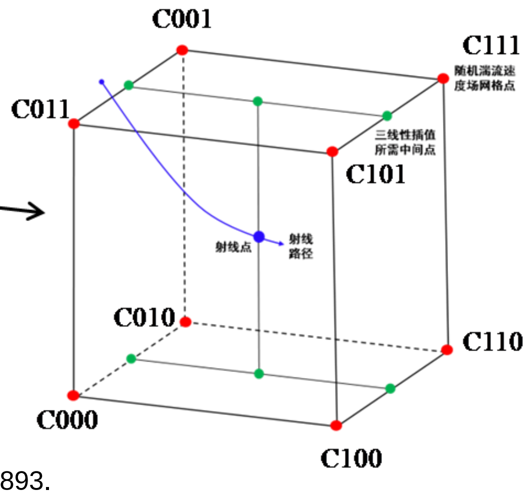
No turbulence:
$$V_0(i)=(V_{0x}\ \ V_{0y}\ \ 0)$$
Turbulence:
$$V_0(i)=(V_{0x}+u'\ \ V_{0y}+v'\ \ w')$$

Trilinear interpolation—performed on the random turbulent velocities into the ray path

$$\begin{aligned} C=&C_{000}(1-x_d)(1-y_d)(1-z_d)+C_{100}x_d(1-y_d)(1-z_d)\\ &+C_{010}(1-x_d)y_d(1-z_d)+C_{001}(1-x_d)(1-y_d)z_d\\ &+C_{101}x_d(1-y_d)z_d+C_{011}(1-x_d)y_dz_d\\ &+C_{110}x_dy_d(1-z_d)+C_{111}x_dy_dz_d \end{aligned}$$

$$x_d=\frac{x-x_0}{x_0-x_1}\qquad y_d=\frac{y-y_0}{y_0-y_1}\qquad z_d=\frac{z-z_0}{z_0-z_1}$$

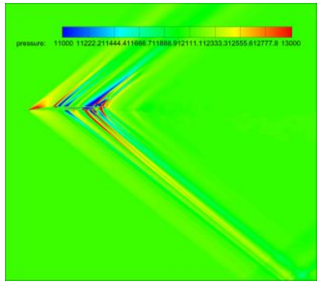


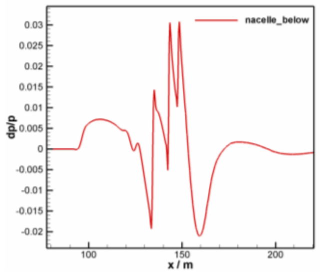


[1] YAMASHITA H, OBAYASHI S. Sonic Boom Variability Due to Homogeneous Atmospheric Turbulence. Journal of Aircraft,2009, 46(6): 1886-1893.

3. Effects of atmospheric turbulence

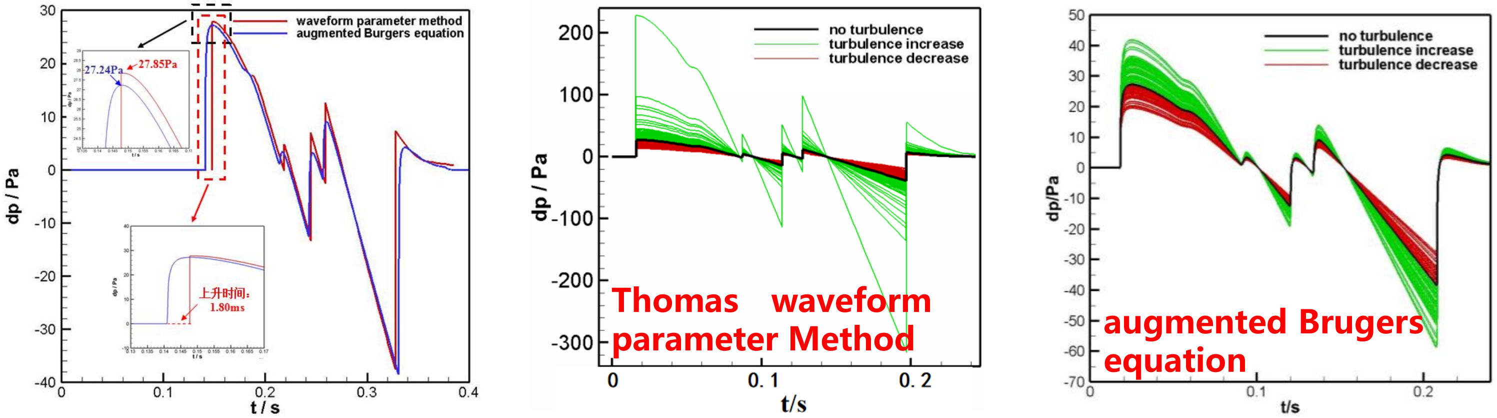
➢ 1D fast prediction method with low reliability



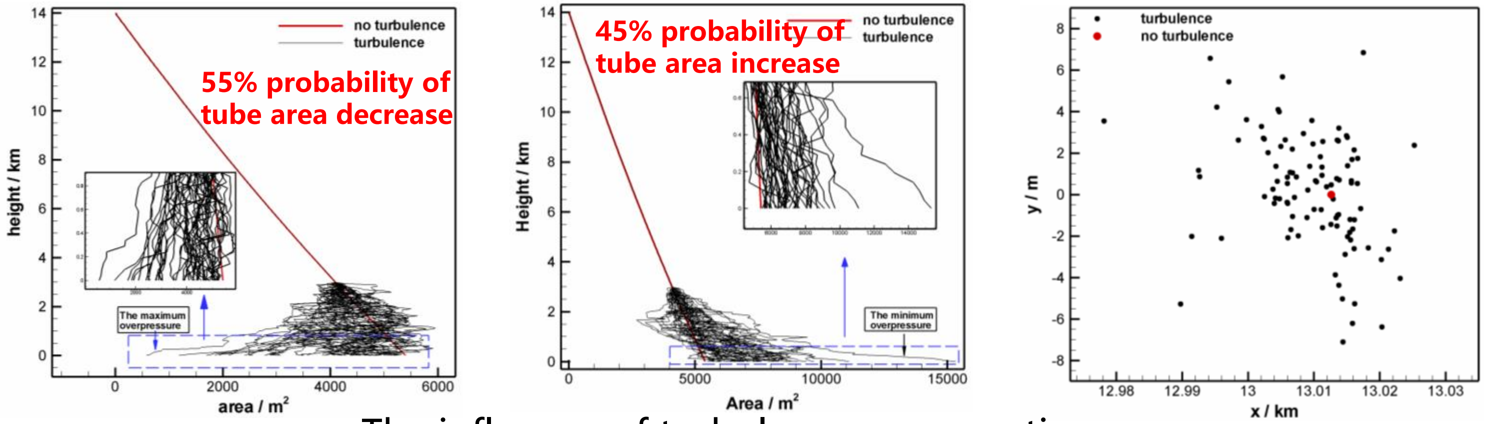


- ▸Cruise: Ma=1.6
  H=15km
  α=4°
- ▸Weight: 130t
- ▸Passengers: 100
- ▸Length: 67m
- ▸Height of ABL: h=3.0km
- ▸RMS of turbulence: V_{rms}=2.5m/s
- ▸Reflection factor: G_{ref}=2.0

Illustration of the configuration of supersonic civil transport



The influence of turbulence on the amplitude of sonic boom



The influence of turbulence on acoustic rays

- ☐ The influence of turbulence on amplitude and path can be obtained.
- ☐ The 1D fast prediction method **cannot explain** the **distortion of sonic boom.**

[1] WANG D, LENG Y, YANG L, et al. Atmospheric turbulence effects on sonic boom propagation based on augmented Burgers equation. Acta Aeronautica et Astronautica Sinica , 2023, 44(02): 71-83.

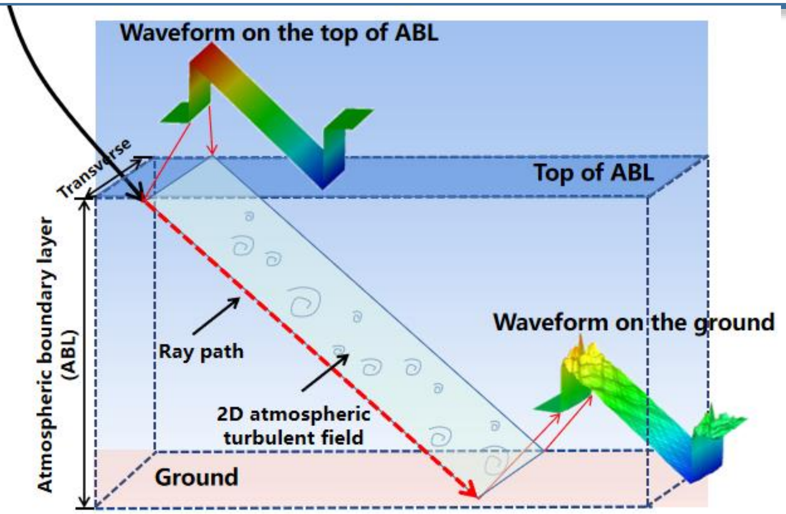
3. Effects of atmospheric turbulence

➢ Multi-dimensional prediction method with high reliability

3D KZK（Khokhlov- Zabolotskaya-Kuznetsov）equation

$$\frac{\partial P}{\partial \sigma} = -\frac{1}{2B}\frac{\partial B}{\partial \sigma}P + P\frac{\partial P}{\partial \tau} + \frac{1}{\Gamma}\frac{\partial^2 P}{\partial \tau^2} + \sum_j \frac{C_j}{1+\theta_j \frac{\partial}{\partial \tau}}\frac{\partial^2 P}{\partial \tau^2} + D\int_{-\infty}^{\tau}\left(\frac{\partial^2 P}{\partial \xi^2} + \frac{\partial^2 P}{\partial \eta^2}\right)d\tau'' + \frac{M_s}{2D}\frac{\partial P}{\partial \tau} + \frac{M_c}{2D}\frac{\partial P}{\partial \tau} - M_x\frac{\partial P}{\partial \xi} - M_y\frac{\partial P}{\partial \eta}$$

Augmented Burgers equation | diffraction term | wind fluctuation term | temperature fluctuation term | transportation term

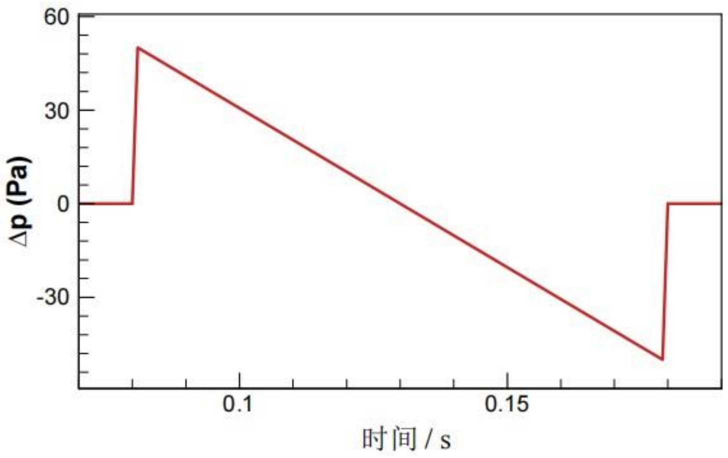


Schematic diagram of sonic boom propagation in atmospheric boundary layer

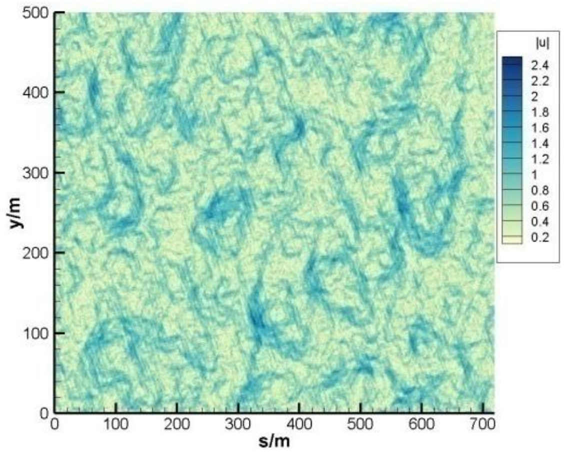
- ✓ differaction term：2nd Crank-Nicolson scheme
- ✓ wind fluctuation term：5th order WENO scheme
- ✓ temperature fluctuation term：5th order WENO scheme
- ✓ transportation term：5th order WENO scheme
- ✓ ray direction：Runge-Kutta scheme
- ✓ Periodic boundary conditions are applied in the transverse direction

3. Effects of atmospheric turbulence

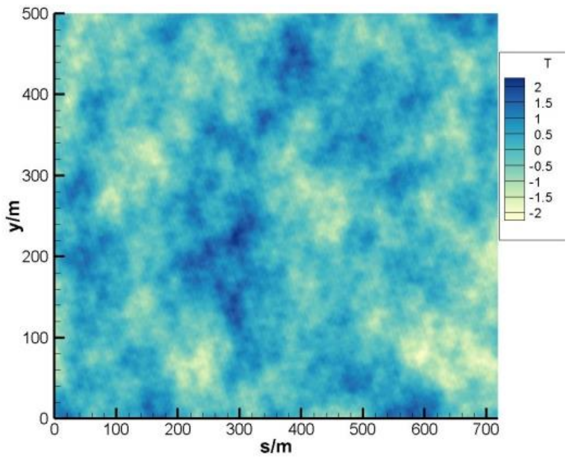
➢ Caeses —— a typical N-waveform



Waveform on the top of ABL

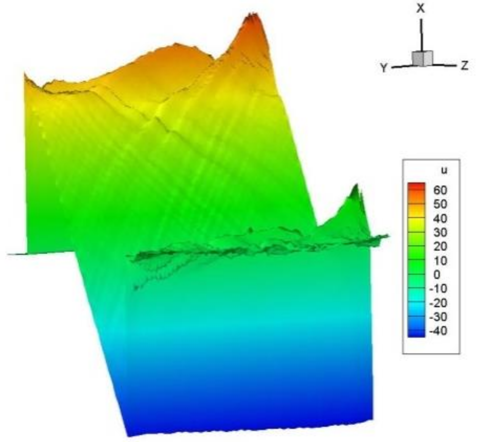


Wind fluctuation field

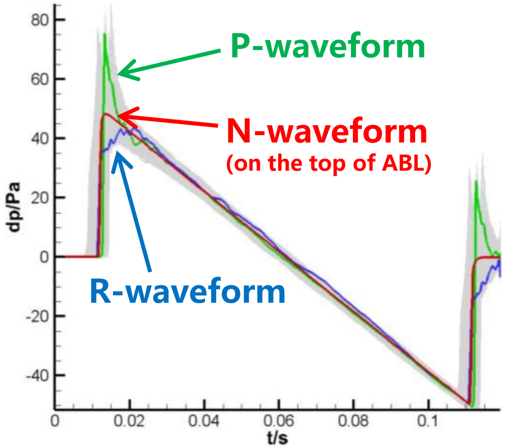


Temperature fluctuation field

- overpressure：50Pa
- duration time：0.1s
- rise time：0.001s
- height of ABL：500m
- Standard deviation of wind fluctuation：1.0m/s
- Standard deviation of temperature fluctuation：1.0K
- outer turbulence scale：40m



The predicted distorted waveform



Typical P-waveform and R-waveform

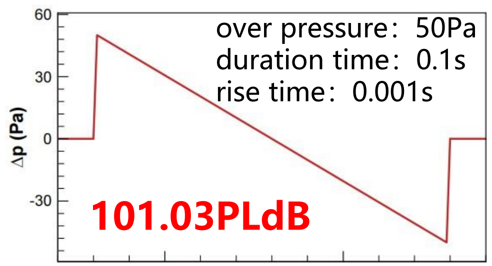
3. Effects of atmospheric turbulence

➢ Effects of atmospheric turbulent intensity on sonic boom

- ✓ Standard deviation of wind fluctuation:

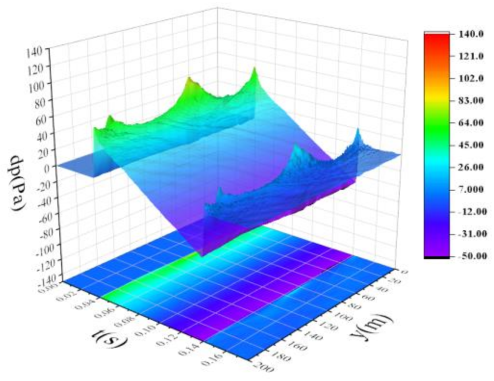
  0.5、1.0、2.0 m/s

- ✓ Standard deviation of temperature fluctuation: 1.0 K
- ✓ Height of ABL: 1,000 m

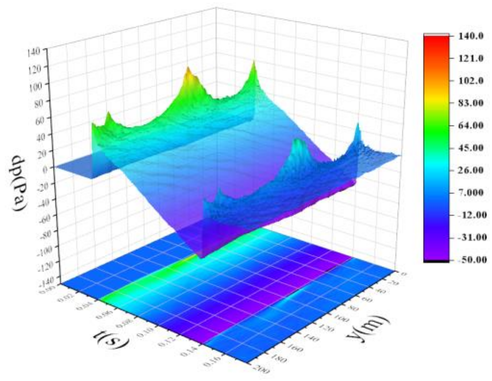


Waveform on the top of ABL

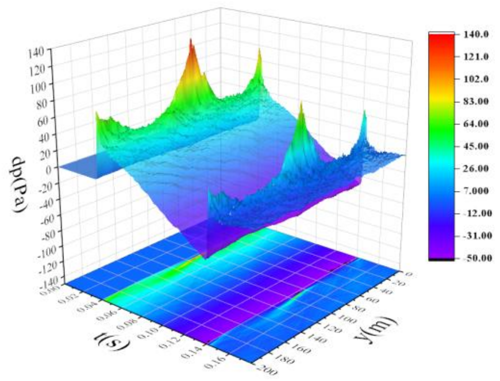
- ✓ Outer turbulence scale: 40m
- ✓ Fourier modes: 400
- ✓ Transverse range: 200 * 200 m^2
- ✓ Grid spacing: 1.0m
- ✓ **Total grids: 80 million**
- ✓ **Total data on ground: 40 thousand**



$v'_{sd.} = 0.5 m/s$



$v'_{sd.} = 1.0 m/s$



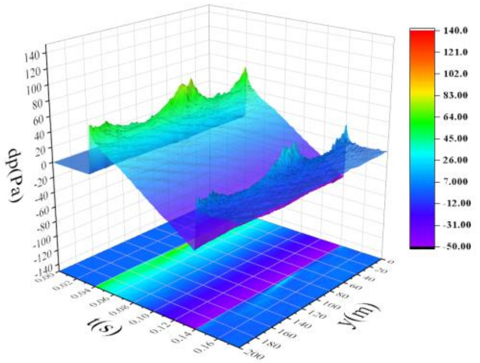
$v'_{sd.} = 2.0 m/s$

$v_{sd.}$(m/s)	increase	decrease	P_{paek} range	Ave. P_{peak}	Sd. P_{peak}	Max. PLdB
0.5	51.19%	48.81%	39.86 ~ 91.03	51.90	7.93	**107.97**
1.0	54.93%	45.07%	38.83 ~ 113.85	53.55	10.14	**110.27**
2.0	63.37%	36.63%	37.76 ~ 146.23	56.67	13.40	**111.68**

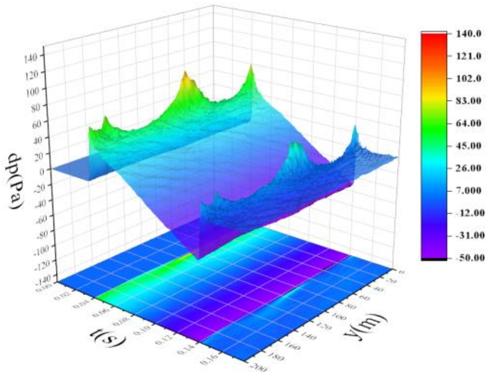
3. Effects of atmospheric turbulence

➢ Effects of atmospheric turbulent intensity on sonic boom

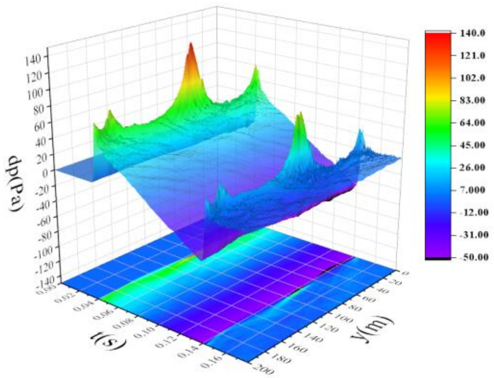
- ✓ Standard deviation of wind fluctuation：1.0 m/s
- ✓ Standard deviation of temperature fluctuation：**0.5、1.0、2.0 K**
- ✓ Height of ABL：1,000 m



$T'_{sd.} = 0.5K$



$T'_{sd.} = 1.0K$



$T'_{sd.} = 2.0K$

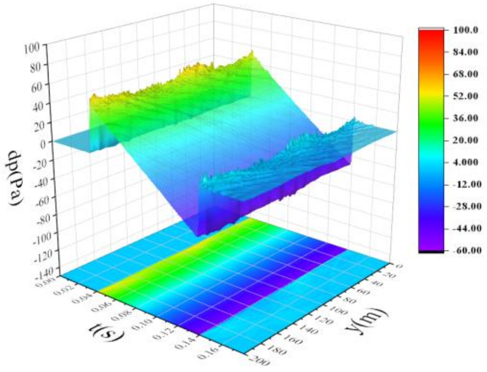
$T_{sd.}$(k)	increase	decrease	P_{paek} range	Ave. P_{peak}	Sd. P_{peak}	Max. PLdB
0.5	53.96%	46.04%	39.32 ~ 95.80	52.55	8.25	**108.36**
1.0	54.93%	45.07%	38.83 ~ 113.85	53.55	10.14	**110.27**
2.0	59.57%	40.43%	37.19 ~ 148.15	55.64	13.56	**112.38**

- ☐ The greater disturbance of wind and temperature field, the more severe distortion of sonic boom

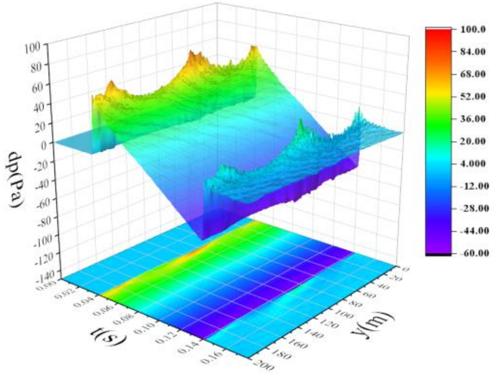
3. Effects of atmospheric turbulence

➢ Effects of atmospheric turbulent intensity on sonic boom

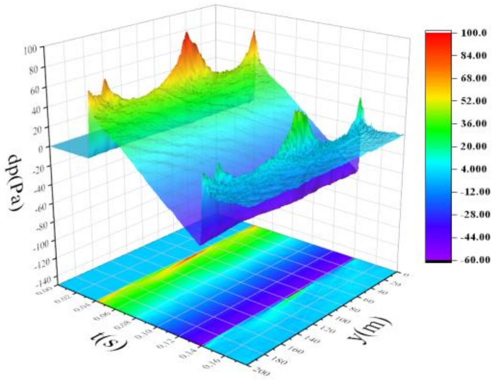
- ✓ Standard deviation of wind fluctuation：1.0 m/s
- ✓ Standard deviation of temperature fluctuation：1.0 K
- ✓ Height of ABL：**500、800、1,000 m**



$H = 500m$



$H = 800m$



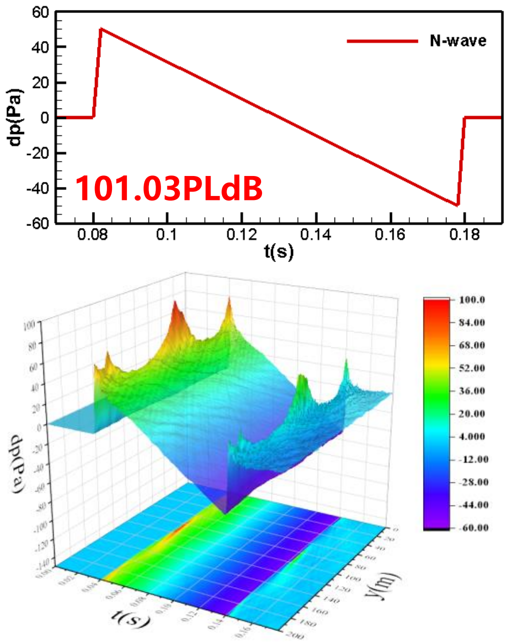
$H = 1,000m$

height/m	increase	decrease	P_{paek} range	Ave. P_{peak}	Sd. P_{peak}	Max. PLdB
500	57.43%	42.57%	39.88 ~ 89.34	51.73	5.69	107.47
800	53.25%	46.75%	38.34 ~ 103.32	52.81	8.77	109.43
1000	54.93%	45.07%	38.83 ~ 113.85	53.55	10.14	110.27

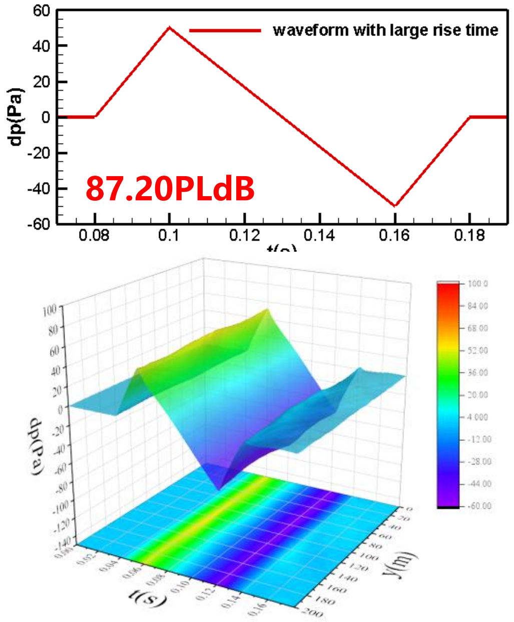
□ The distortion of sonic boom becomes more severe as the atmospheric boundary layer height increases

3. Effects of atmospheric turbulence

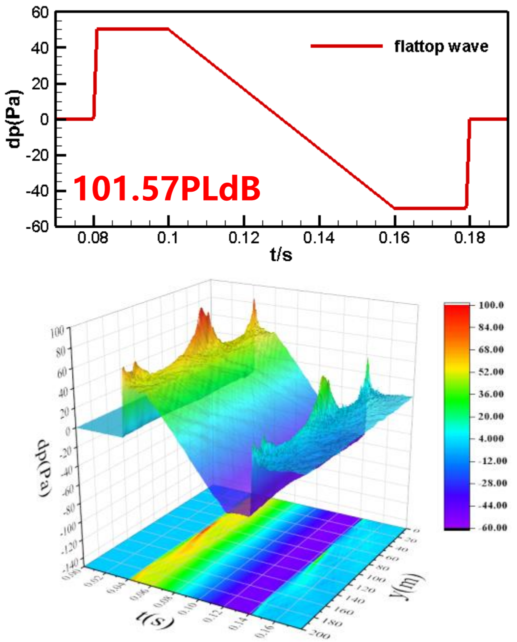
➢ Impact on the different types of sonic boom



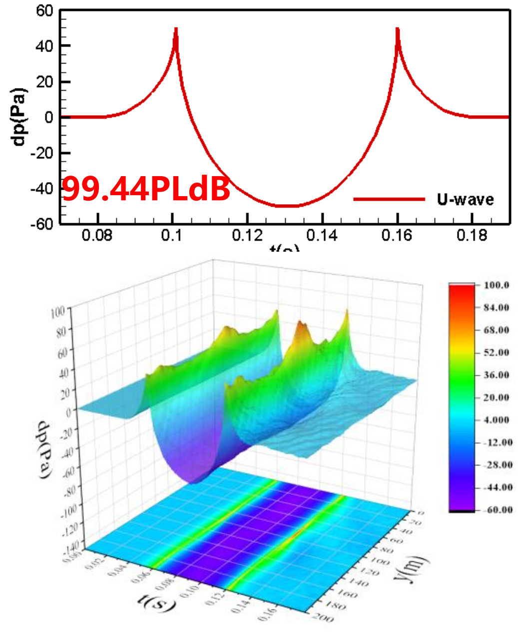
N-wave



Waveform with large rise time



flattop wave



U-wave

type	increase	decrease	P_{paek} range	Ave. P_{peak}	Sd. P_{peak}	Max. PLdB	Max.growth rate
N-wave	54.93%	45.07%	38.83 ~ 113.85	53.55	10.14	110.27	**9.15%**
waveform with large rise time	30.34%	69.66%	43.29~56.07	48.64	2.61	90.38	**3.65%**
flattop wave	99.0%	1.0%	48.68~116.10	58.65	7.99	110.42	8.71%
U-wave	20.74%	79.26%	30.00~85.81	44.14	8.69	103.90	4.49%

Outline

Backgrounds

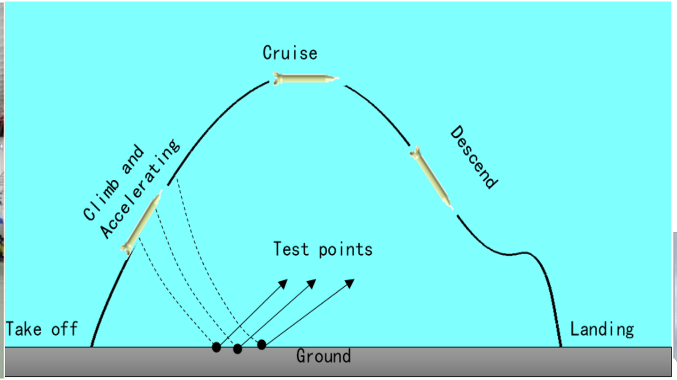
Introduction of ARI_Boom in-house code

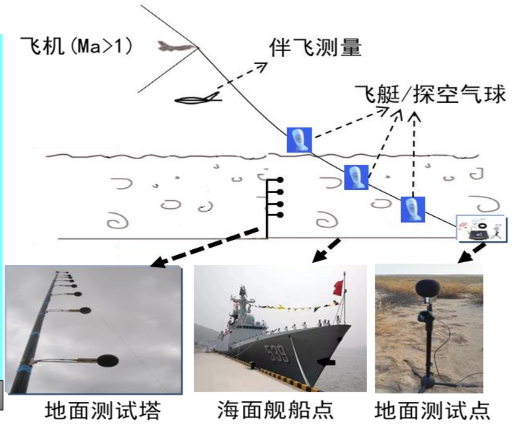
Effects of atmospheric turbulence

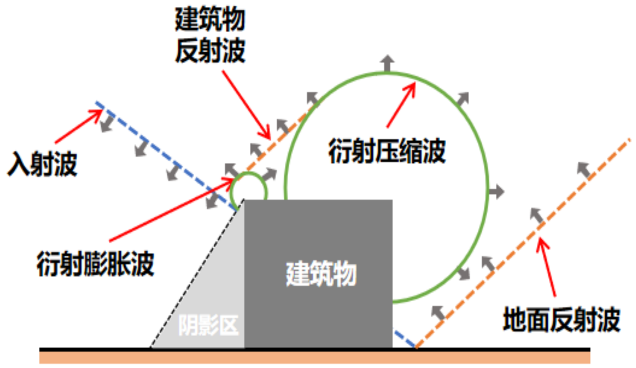
Future work of ARI_Boom

4. Future work of ARI_Boom

- **Efficient and reliable numerical methods for 3D turbulence effects**
- **Ground physical experiments on the interaction between turbulence and sonic boom, and improve the numerical model**
  - wind tunnel
  - sonic boom simulator
- **Flight test to obtain real data for the code validation**
- **Effects of the complex terrain on the propagation of sonic boom near the ground**







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Thank you for attention！