The first scientific evidence for the hail cannon

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Foundations of computational science in Kraków

Institute of Computer Science, AGH University
located next to the Banach space

The poster says: "Keep out from the Banach space!"

Stefan Banach studied in Kraków

39,200 results from Web of Science for Banach space

The LU decomposition was introduced by the Polish astronomer Tadeusz Banachiewicz in 1938 (who worked at **AGH University**)
`https://en.wikipedia.org/wiki/LU_decomposition`

10,013 results from Web of Science for LU method

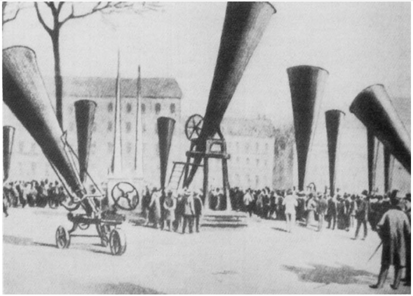
Hail cannon - motivation

Grapevines in France's Burgundy region damaged by a hailstorm.

The idea of the hail cannon is to create a sequence of shock waves to prevent the formation of clouds before the hailstorm.

The hail cannon was invented in 1896
by the Austrian wine grower Albert Stiger.
His apparent success at repelling hail from his vineyards
led to a rapid proliferation of similar devices,
with more than 10,000 in use by 1900.

Hail cannon

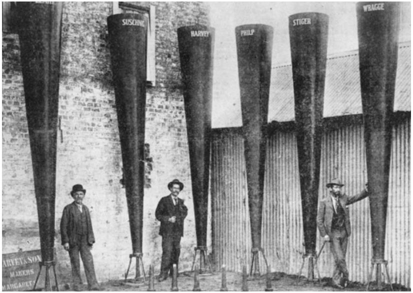


International congress on hail shooting, Lyon, 1901

A hail cannon is a shock wave generator claimed to disrupt the formation of hailstorms in the atmosphere.
https://en.wikipedia.org/wiki/Hail_cannon

Stanley A. Changnon Jr. and J. Loreena Ivens,
History Repeated: The Forgotten Hail Cannons of Europe,
Bulletin of the American Meteorological Society,
Volume 62: Issue 3 (1981)

Hail cannon reputation 1902

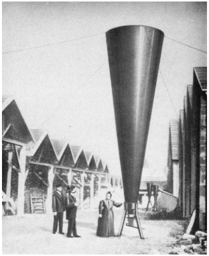


Number of experts in whose opinion ...

.... cannonading is entirely not working	5 (10%)
.... the efficacy is only doubtful	13 (26%)
.... the efficacy is not only doubtful, but improbable	15(30%)
.... the efficacy is still doubtful, but probable	9(18%)
.... cannonading is working	8 (16%)
Total	50 (100%)

Experts opinions on hail shooting in 1902

Hail cannon reputation 1975



Number of scientists who believe ...

... the technology is a failure	27 (5%)
... do not know if there is any capability to suppress hail	318 (59%)
... the suppression capability is between 1% and 25%	95 (18%)
.... the suppression capability is between 26% and 82%	94 (18%)
Total	534 (100%)

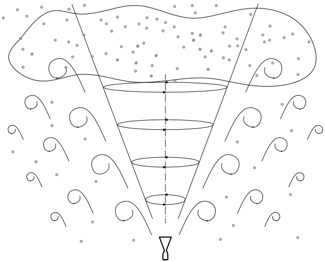
Scientists opinions on hail shooting in 1975

Modern Hail cannons

Hail cannon Inopower https://www.inopower.be/
(Photos by Maciej Woźniak)

Modern hail cannons employ a mixture of acetylene and oxygen to ignite a sequence of explosions in the lower chamber traveling through the neck and into the cone of the cannon, creating shock waves.

Modern Hail cannons



Hail cannon Inopower https://www.inopower.be/

The shock wave produced by the ignition of an acetylene-air mixture is directed vertically upward through the widening conical outlet tube.

The shock waves propagate upwards to the cloud,
and they are supposed to prevent the formation of the cloud.

No scientific evidence (so far)

`https://en.wikipedia.org/wiki/Hail_cannon`

"There is no evidence in favor of the effectiveness of these devices."

"The use of cannons is a waste of money and effort"

[1] Jon Wieringa, Jon, Iwan Holleman,
If cannons cannot fight hail, what else?
Meteorologische Zeitschrift 15 (6) (2006) 659–669

"Thunder is a much more powerful sonic wave,
and is usually found in the same storms that generate hail,
yet it doesn't seem to disturb the growth of hailstorms."

[2] John Curran,
Vermont Orchard wakes the neighbors with hail cannon.
Sun Journal, Associated Press. Posted September 23 (2008).

Hail cannon simulations with IGA-ADS

IGA-ADS open-source parallel shared-memory C++ code for simulations of transient phenomena, with the following features:

- it supports isogeometric finite element method discretizations;
- it works on tensor product grids;
- it employs alternating-directions (ADS) linear cost $\mathcal{O}(N)$ solver;
- it uses explicit time-integration scheme;
- it works for 2D/ 3D problems;
- it supports scalar, vector fields, and systems of PDEs;

```
$ git clone https://github.com/marcinlos/iga-ads
$ mkdir build-dir
$ cmake -S. -B build-dir
$ cmake -build build-dir -parallel
$ cmake -install install build-dir
```

LAPACK, Boost 1.58, Galois 2.2.1, GCC 5.3.1, CMake

Marcin Łoś, Maciej Woźniak, Maciej Paszyński, Andrew Lenharth, Keshav Pingali, IGA-ADS : Isogeometric Analysis FEM using ADS solver, **Computer & Physics Communications** 217 (2017) 99-116.

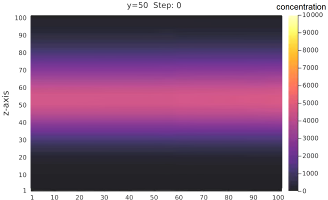
Advection-diffusion equations

$$\underbrace{\frac{\partial u}{\partial t}}_{\text{time evolution}} = -\underbrace{(\mathbf{b}\cdot\nabla)u}_{\text{advection ``wind"}} + \underbrace{\nabla\cdot(\mathbf{K}\nabla u)}_{\text{diffusion}} \quad \text{in } \Omega\times(0,T] \qquad (1)$$

$$\underbrace{u = u_0}_{\text{initial hail cloud}} \quad \text{in } \Omega\times 0 \qquad (2)$$

$$\underbrace{\nabla u\cdot n = 0}_{\text{``sufficiently large domain" boundary condition}} \quad \text{in } \partial\Omega\times(0,T] \qquad (3)$$

where $u(x,y,z;t)$ is the cloud vapor concentration scalar field,
Our initial configuration $u(x,y,z;0) = u_0(x,y,z)$
is the cloud "fixed" at the height of $3/4$ of the domain.
$\Omega = [0,100m]\times[0,100m]\times[0,100m]$.



Advection-diffusion equations

$$\underbrace{\frac{\partial u}{\partial t}}_{\text{time evolution}} = -\underbrace{(\mathbf{b}\cdot\nabla)u}_{\text{advection ``wind"}} + \underbrace{\nabla\cdot(\mathbf{K}\nabla u)}_{\text{diffusion}} \quad \text{in } \Omega\times(0,T] \tag{4}$$

$$\underbrace{u = u_0}_{\text{initial hail cloud}} \quad \text{in } \Omega\times 0 \tag{5}$$

$$\underbrace{\nabla u\cdot n = 0}_{\text{``sufficiently large domain" boundary condition}} \quad \text{in } \partial\Omega\times(0,T] \tag{6}$$

In the atmospheric modeling there are two types of diffusion: *molecular diffusion* and *turbulent diffusion*.

The *turbulent diffusion* is quicker and non isotropic.

In a *stable atmosphere*:

- the lower masses are denser and cooler than the upper masses
- the horizontal turbulence diffusion is greater than the vertical diffusion (no transfer between layers)

$K_x = K_y = 1.0$ are the horizontal diffusion coefficients,

$K_z = 0.1$ is the vertical diffusion.

Advection-diffusion equations

$$\underbrace{\frac{\partial u}{\partial t}}_{\text{time evolution}} = -\underbrace{(\mathbf{b}\cdot\nabla)u}_{\text{advection “wind"}} + \underbrace{\nabla\cdot(\mathbf{K}\nabla u)}_{\text{diffusion}} \text{ in } \Omega\times(0,T] \quad (7)$$

$$\underbrace{u = u_0}_{\text{initial hail cloud}} \quad \text{in } \Omega\times 0 \quad (8)$$

$$\underbrace{\nabla u\cdot n = 0}_{\text{“sufficiently large domain" boundary condition}} \quad \text{in } \partial\Omega\times(0,T] \quad (9)$$

b represents *assumed* air movement

$$(b_x(x,y,z;t), b_y(x,y,z;t), b_z(x,y,z;t)) = (0,0,cannon(x,y,z;t))$$

$$cannon(x,y,z;t) = const*(1-z)*$$
$$sin(10*\pi*x)*sin(10*\pi*y)*max(0,sin(\pi*t/10)),$$

for $t = s - 100$, where s is the time step size.

We run the cannon from time step 100 until 1000, we shoot for 10 time steps with a function $(1-z)*sin(10*\pi*x)*sin(10*\pi*y)$ that runs in time like $max(0,sin(\pi*t/10))$ (45 shoots)

Discrete weak formulation for IGA-ADS code

$$\underbrace{\frac{u^{t+1}-u^{t}}{\tau}}_{\text{Forward Euler explicit method}} = \nabla \cdot (\mathbf{K}\nabla u^{t}) - (\mathbf{b}\cdot\nabla)u^{t}$$

We "average" PDE with test functions v being quadratic B-splines

$$\int_{\Omega} u^{t+1} v d\mathbf{x} = \int_{\Omega} u^{t} v d\mathbf{x} - \tau \left(\underbrace{\int_{\Omega} \mathbf{K}\nabla u^{t} \cdot \nabla v d\mathbf{x}}_{\text{integration by parts}} + \int_{\Omega} \mathbf{b}\cdot\nabla u^{t} v d\mathbf{x} \right) \forall v \in V$$

$$\left(u^{t+1}, v\right) = \left(u^{t}, v\right) - \tau \left(\mathbf{K}\nabla u^{t}, \nabla v\right) - \tau \left(\mathbf{b}\cdot\nabla u^{t}, v\right) \forall v \in V$$

$$\left(u^{t+1}, v\right) = \left(u^{t}, v\right) - \tau \left(\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0.1 \end{bmatrix} \nabla u^{t}, \nabla v \right) - \tau \left(b_z \frac{\partial u}{\partial z}, v \right) \forall v \in V$$

IGA-ADS explicit dynamics implementation

$$\left(u^{t+1}, v\right) = \left(u^t, v\right) - \tau\left(\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0.1 \end{bmatrix} \nabla u^t, \nabla v\right) - \tau\left(b_z \frac{\partial u}{\partial z}, v\right) \forall v \in V$$

```
void compute_rhs(int iter)
  auto& rhs = u; zero(rhs);
  for(auto e:elements()) {
    auto U = element_rhs(); double J = jacobian(e);
    for (auto q :  quad_points()) {
      double w = weight(q);
      for (auto a :  dofs_on_element(e)) {
        auto aa = dof_global_to_local(e, a);
        value_type v = eval_basis(e, q, a);
        value_type u = eval_fun(u_prev, e, q);
        double grad = 1.*u.dx * v.dx +
        1.*u.dy * v.dy + 0.1*u.dz * v.dz;
        double val = u.val * v.val - steps.dt * grad +
          steps.dt *  cannon(e[1])*u.dz*v.val;
        U(aa[0], aa[1]) += val * w * J; } }
    update_global_rhs(rhs, U, e); }
```

Numerical results

The simulations are executed on a laptop.
The whole simulation takes around 1 hour on Corsair Vengeance LPX, DDR4, 64 GB (2x32GB), 3200MHz, CL16 with processor AMD Ryzen 9 - 3900X with 12 physical cores (24 virtual cores).
Mesh size [0,100m]x[0,100m]x[0,100m]. 10,000 time steps.

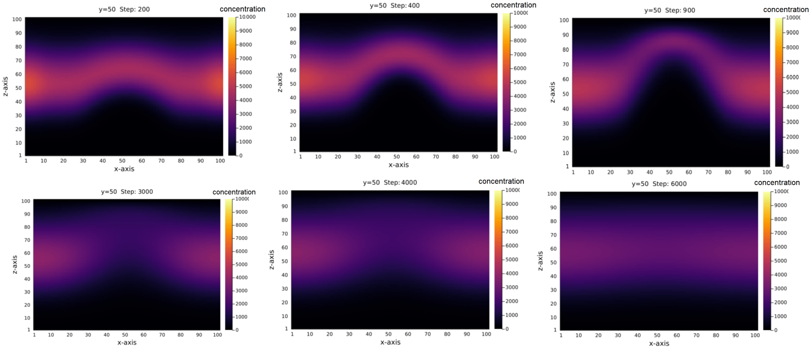


Figure: Reduction of the cloud vapor by generated shock waves. Side view.

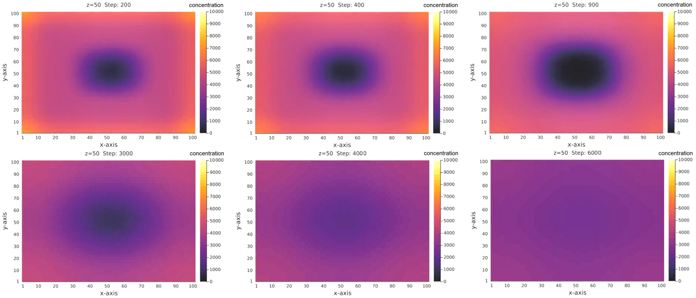


Figure: Reduction of the cloud vapor by generated shock waves. Top view.

- start generating the shock waves at time step t = 100
- continue this sequence of shock waves until time step t = 1000 (the maximum reduction of the cloud vapor).
- the "hole" in clouds remains there for another 2000 time steps (two times longer than the generation of shock waves)
- next, the neighboring cloud vapor particles return slowly to the center by the diffusion mechanism.

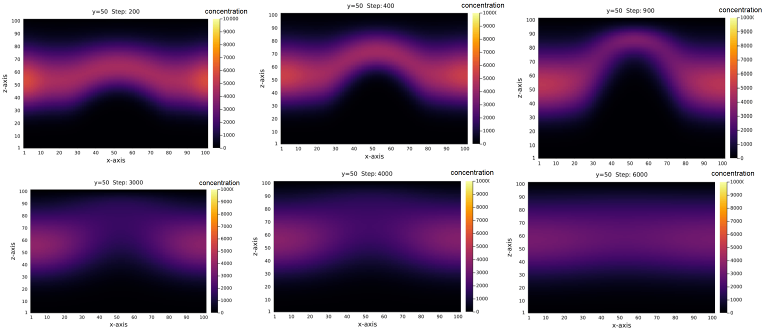


Figure: Reduction of the cloud vapor by generated shock waves. Side view.

We show that a sequence of generated shock waves can move the cloud vapor up and to the sides.

After finishing a sequence of shock wave generation, the "hole" in the cloud remains intact for a long time.

After that time, if the neighboring clouds are still there, the hole is filled with the cloud vapor particles by the diffusion.

Numerical results

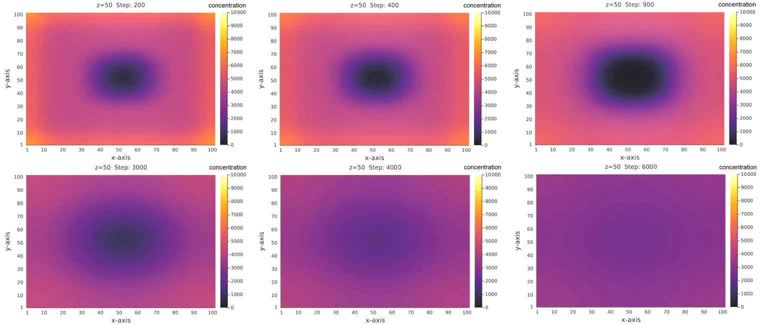
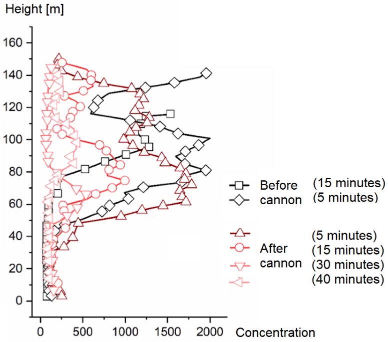


Figure: Reduction of the cloud vapor by generated shock waves. Top view.

We show that generating a sequence of shock waves
can produce a hole in the cloud vapor.

The argument that the thunderstorm is not removing the hailstorm and, thus, the hail cannons are not working *is not valid* since we need to produce a long sequence of shock waves to obtain the desired effect.

Experimental verification



Sequence of explosions, acetylene - air mixture, 1 MPa pressure. 300 shock waves generated in half an hour (1 shoot every 6 seconds)

For the experimental verification we measured the temperature, the humidity, and the particular matter concentration in the vertical profile using the equipment placed on the DJI Matrice 200 V2 drone.

Experimental results agree with numerical experiments

Conclusions

- The first 3D simulational verification of the hail cannon.
- Repeating a sequence of shock waves for a long time significantly reduces cloud vapor for a longer time
- Our model is simple and may require several improvements:
  - computing the advection field resulting from cannon shooting; it requires a solution of the 3D Navier-Stokes equations (N-S solution plugged as the advection field)
  - Including different cloud components and the reaction terms
  - Additional movement of the cloud particles by thermal effects (considering the Navier-Stokes-Boussinesq model)
- Nevertheless, the presented results are very interesting, and they also confirm our experimental findings.

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