# ECEN 3410
# Electromagnetic Waves

1. Uniform plane waves (reflection and transmission through different environments, polarization)
2. Non-uniform plane waves in a coaxial line and quasi-TEM waves in printed lines (microstrip and CPW).
3. Waveguides and resonators that support other modes (field profiles) will be studied:
   - metallic waveguides for RF high power and high-frequency applications (TE,TM),
   - hybrid and evanescent modes in dielectric waveguides (slab guides, rectangular THz dielectric guides, silicon integrated photonics, and optical fibers).
4. Basics of beam propagation (Gaussian beams) for optical and millimeter-wave/THz frequencies.
5. Return to plane waves to study fundamentals of antennas and propagation.

# Maxwell's equations

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S}, \tag{19.5}$$

*[Faraday's law for a fixed contour, Eq. (14.6) = Maxwell's first equation]*

$$\oint_C \mathbf{H} \cdot d\mathbf{l} = \int_S \left(\mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}\right) \cdot d\mathbf{S}, \tag{19.6}$$

*[Generalized Ampère's law, Eq. (19.4) = Maxwell's second equation]*

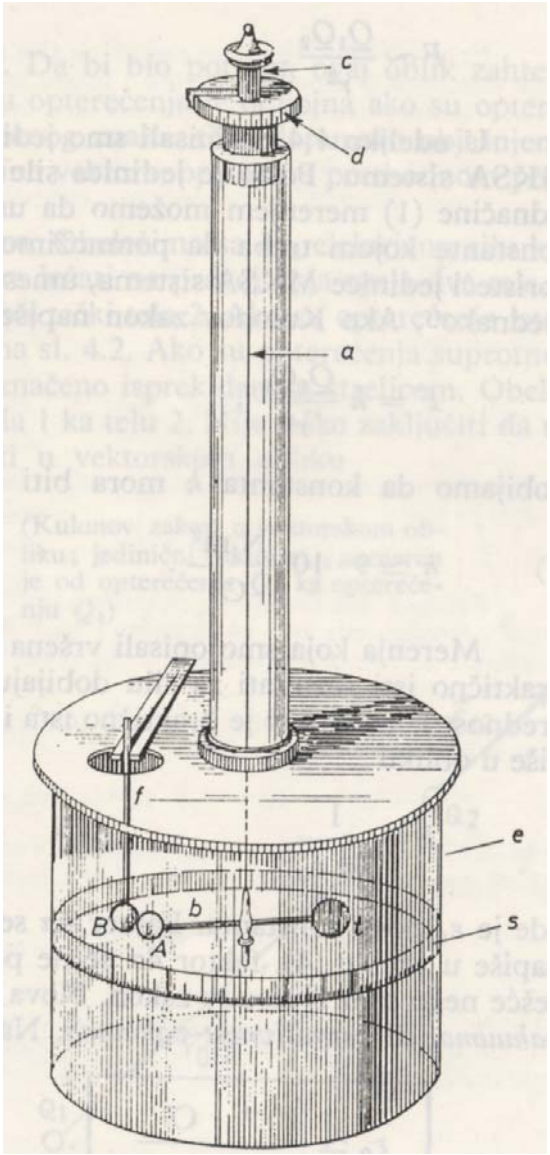
$$\oint_S \mathbf{D} \cdot d\mathbf{S} = \int_v \rho \, dv, \tag{19.7}$$

*[Gauss' law, Eq. (7.20) = Maxwell's third equation]*

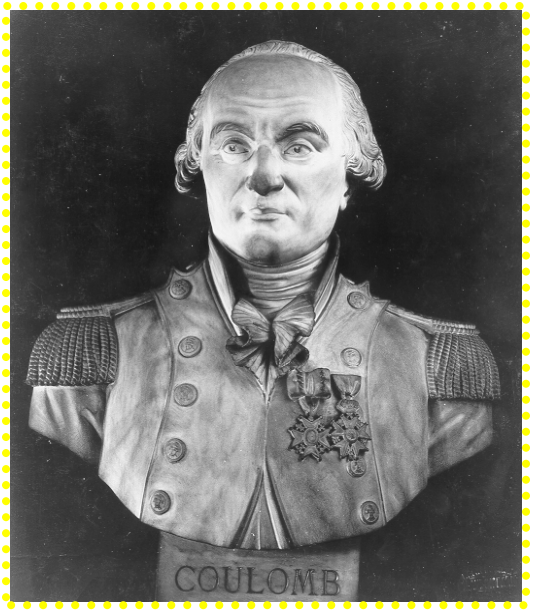
$$\oint_S \mathbf{B} \cdot d\mathbf{S} = 0. \tag{19.8}$$

*[Law of conservation of magnetic flux, Eq. (12.11) = Maxwell's fourth equation]*

# Gauss' law is based on Coulomb's law - MEASURED




Coulomb's torsion balance experiment gave law for electrostatic force:

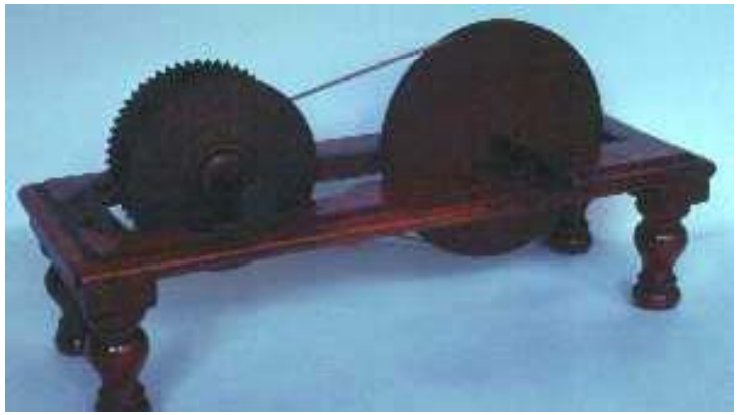



$$\mathbf{F}_{e12} = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r^2}\mathbf{u}_{r12}$$

**Charles Augustin de Coulomb**
**(1736 – 1806)**

# Ampere's law is based on the Biot-Savare law for magnetic forces – MEASURED (~1820)

**Jean-Baptiste Biot**
(1774 – 1862)



**Felix Savart** (1791-1841)

**André-Marie Ampère**
(1775 –1836)
Electrodynamics
Unit of electric current

$$\mathrm{d}\mathbf{F}_{12} = I_2\,\mathrm{d}\mathbf{l}_2 \times \left(\frac{\mu_0}{4\pi}\frac{I_1\,\mathrm{d}\mathbf{l}_1 \times \mathbf{u}_r}{r^2}\right)$$

# Faraday's law – MEASURED (~1860)

**Michael Faraday**
(1791 – 1867)

**Joseph Henry**
(1797 –1878)

# Optics and the speed of light

**Joseph Fraunhofer**
**(**1787 – 1826)

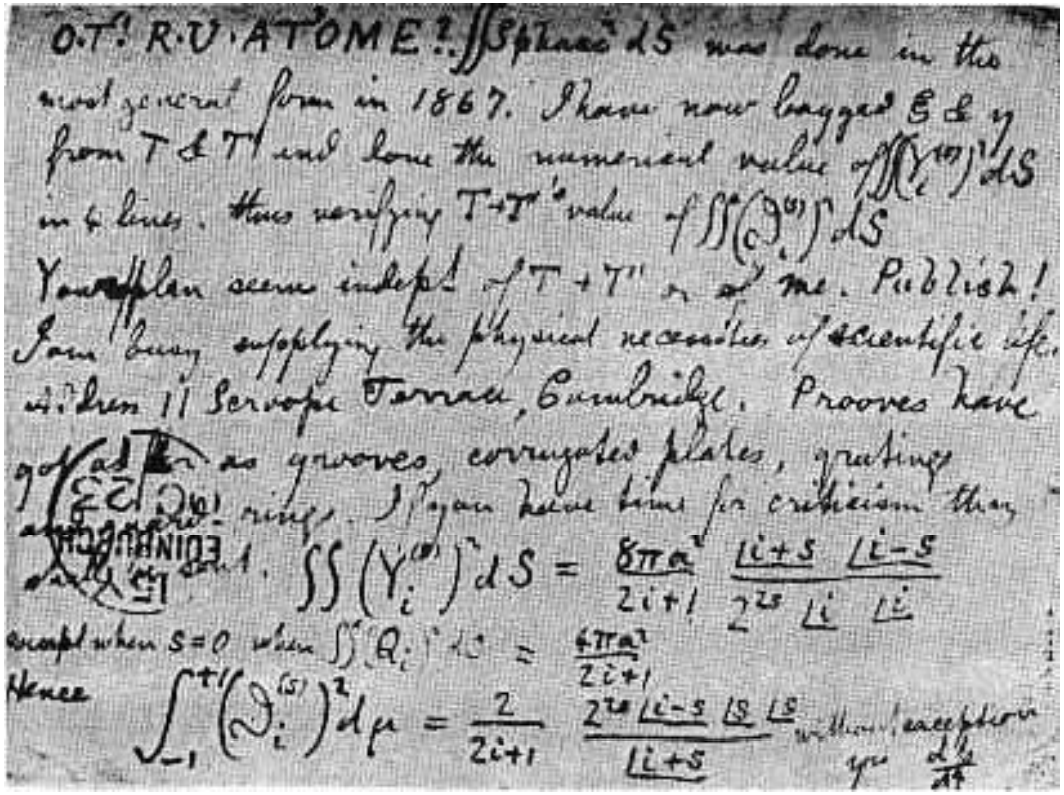
**Augustin-Jean Fresnel**
(1788–1827)

| | | |
|---|---|---|
| 1675 | Romer and Huygens<br>moons of Jupiter | 220,000 m/s |
| 1729 | James Bradley<br>aberration of light | 301,000m/s |
| 1849 | Hippolyte Fizeau<br>toothed wheel | 315,000m/s |
| 1862 | Leon Foucault<br>rotating mirror | 298,000±500 |
| 1907 | Rosa and Dorsey,<br>EM constants | 299,710±30 |
| 1926 | Albert Michelson<br>rotating mirror | 299,796±4 |
| 1950 | Essen and Gordon-Smith,<br>cavity resonator | 299,792.5±3.0 |
| 1958 | K.D. Froome,<br>radio interferometry | 299,792.50±0.10 |
| 1972 | Evenson *et al.*,<br>laser interferometry | 299,792.4562±0.0011 |
| 1983 | 17th CGPM,<br>definition of the meter | 299,792.458 (exact) |

# Maxwell put it all together

## Maxwell's equations are postulated and based on experiment

**James Clerk Maxwell**
(1831 – 1879)



# Maxwell and Heaviside

- 1864: calculated speed of light 310,740,000 m/s
- 1873: Treatise on electricity and magnetism
  - Reduced all previous EM to 20 differential equations with 20 variables
- Oliver Heaviside introduced vector algebra and reduced equations to four

# Heaviside on Maxwell's equations

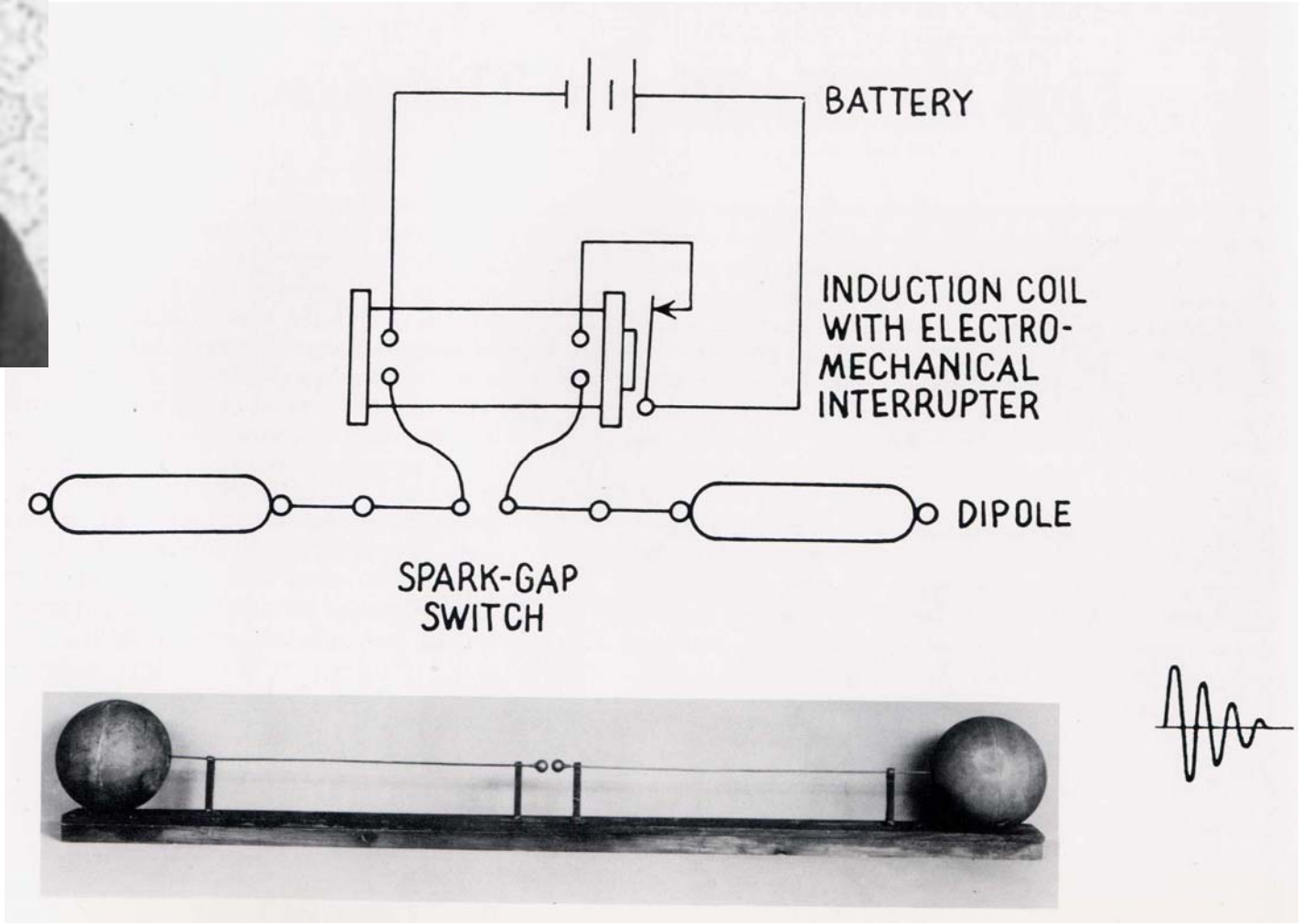
"I remember my first look at the great treatise of Maxwell's when I was a young man... I saw that it was great, greater and greatest, with prodigious possibilities in its power... I was determined to master the book and set to work. I was very ignorant. I had no knowledge of mathematical analysis (having learned only school algebra and trigonometry which I had largely forgotten) and thus my work was laid out for me. It took me several years before I could understand as much as I possibly could. Then I set Maxwell aside and followed my own course. And I progressed much more quickly... It will be understood that I preach the gospel according to my interpretation of Maxwell."

# Heaviside's contributions

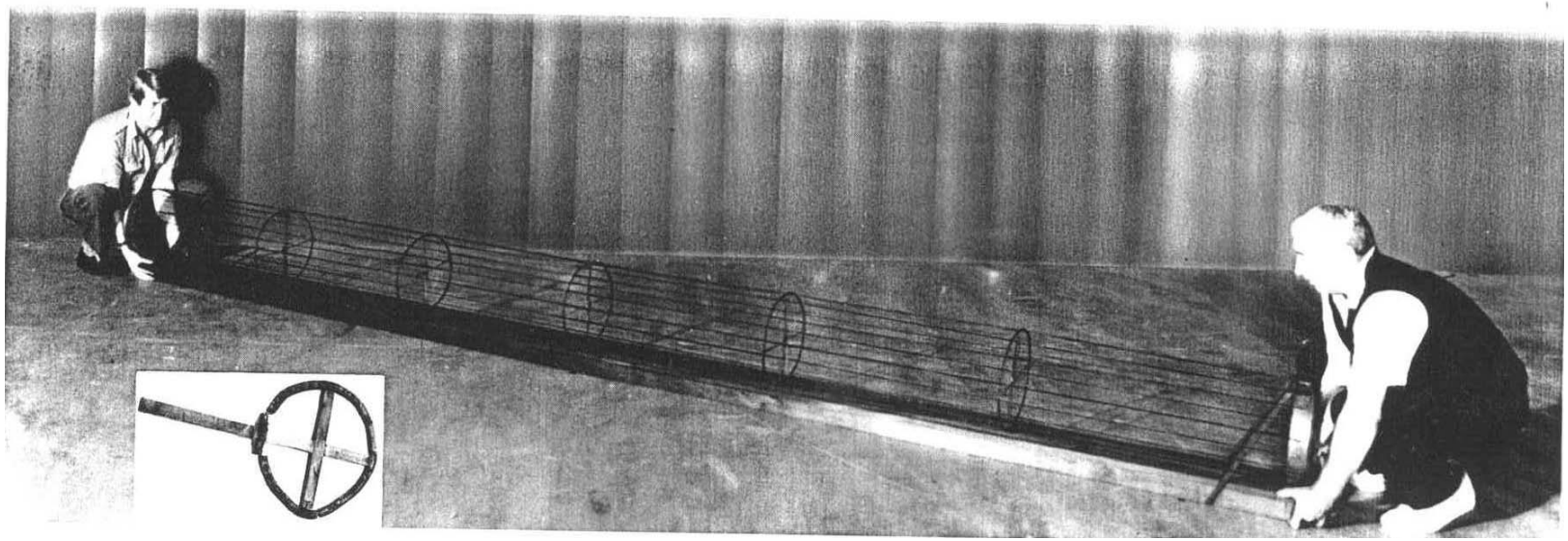
- Transmission line equations
- "Pupin" coils for long-distance signaling
- Laplace transforms
- Vector calculus
- Cherenkov radiation
- Lorentz force
- Poynting vector
- Predicted existence of ionosphere
- Coined the terms:
  - Inductance (February 1885)
  - Conductance (Sept. 1885)
  - Permeability (Sept 1885)
  - Impedance (July 1886)
  - Admittance (Dec. 1887)

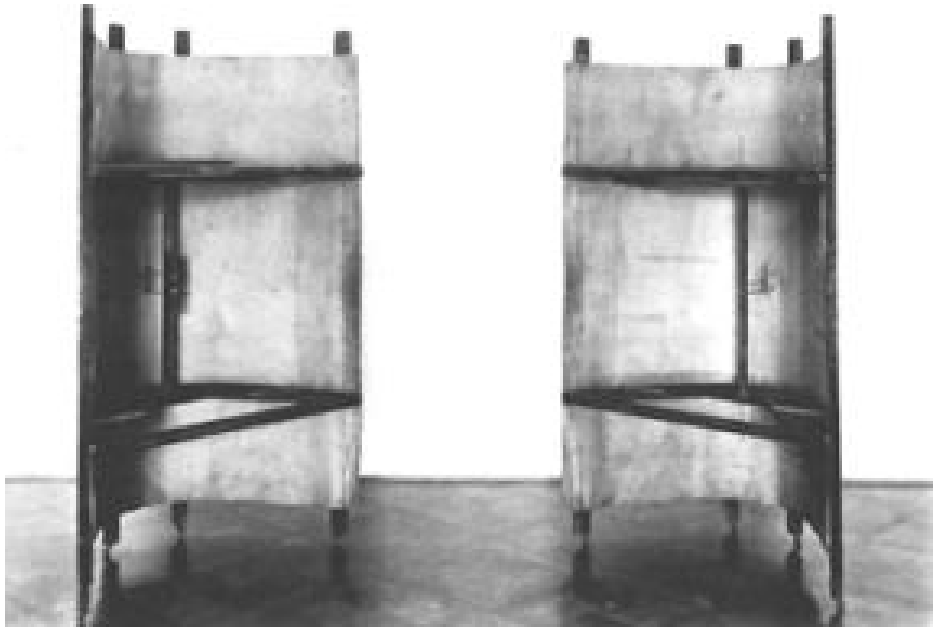
# First radio waves

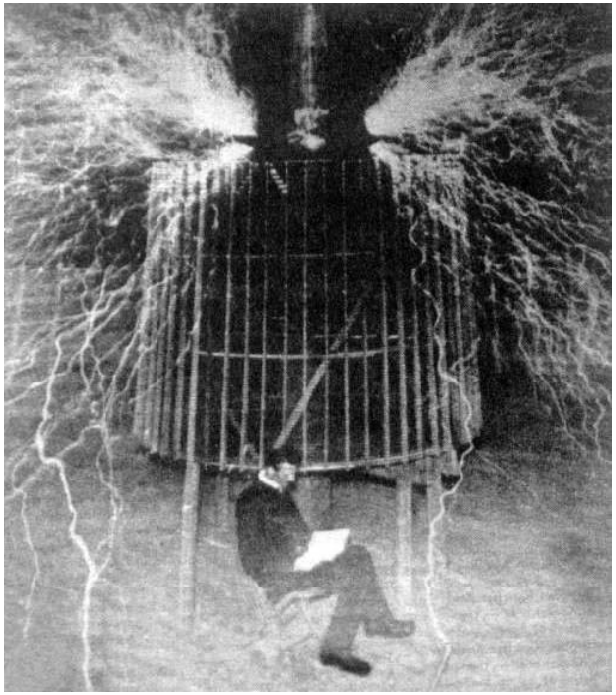
**Heinrich Hertz**
**(**1857– 1894)



# First coax, antennas and polarizers





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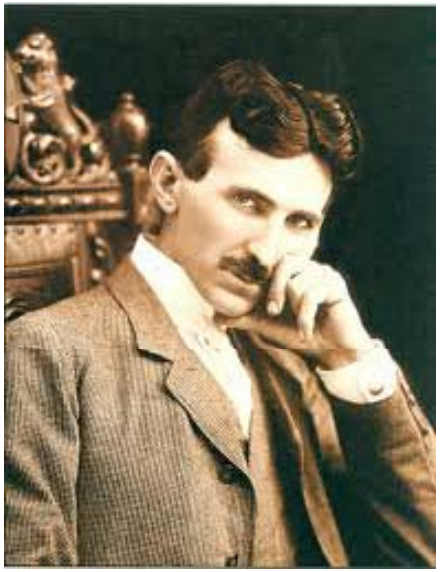
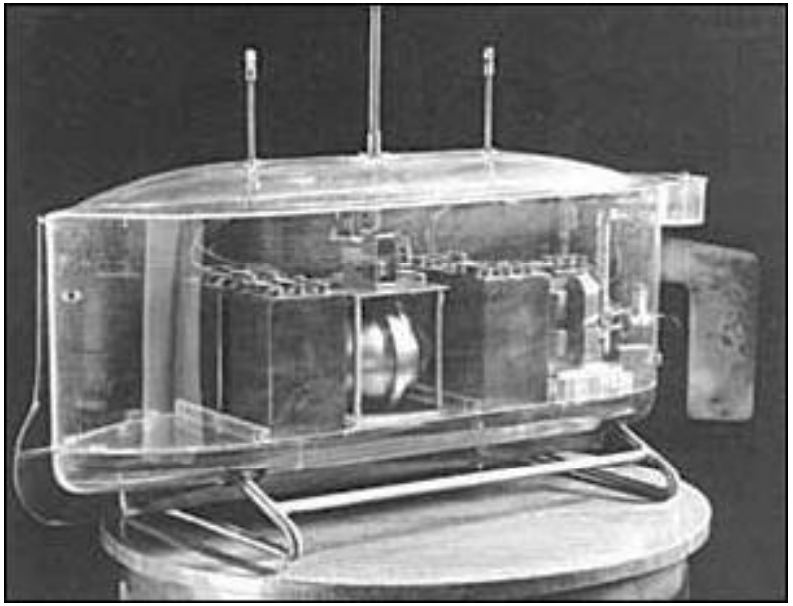
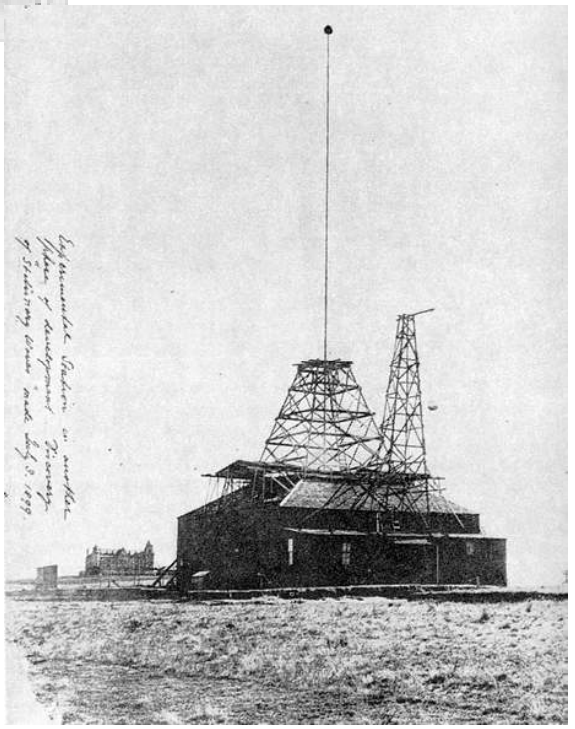
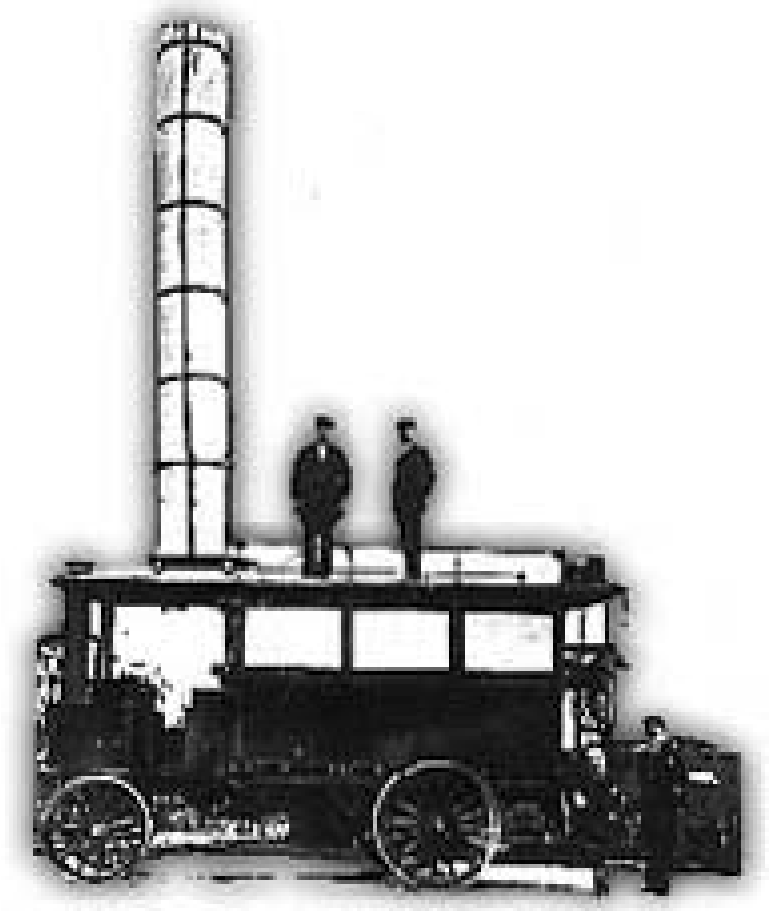






# Not so long ago…



Marconi's mobile radio


Bell Labs mobile radio

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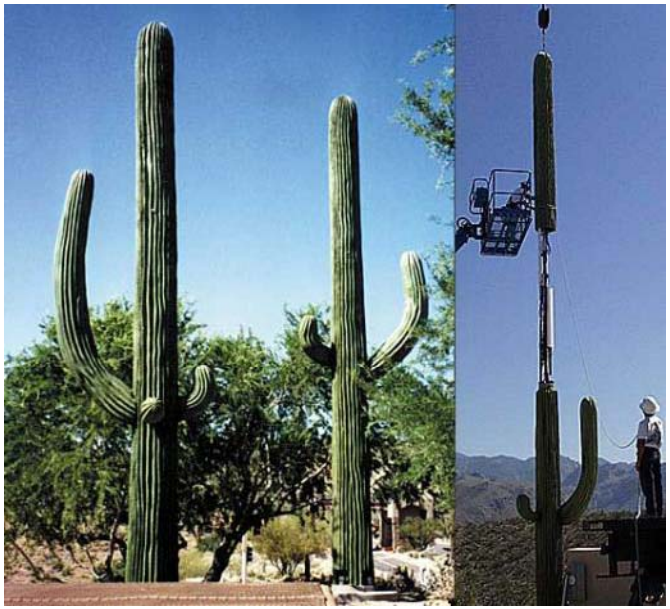
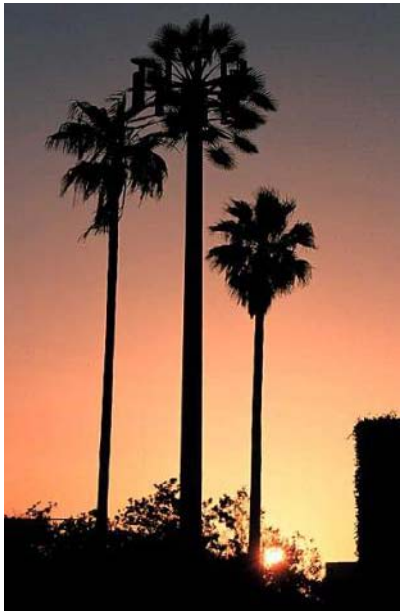
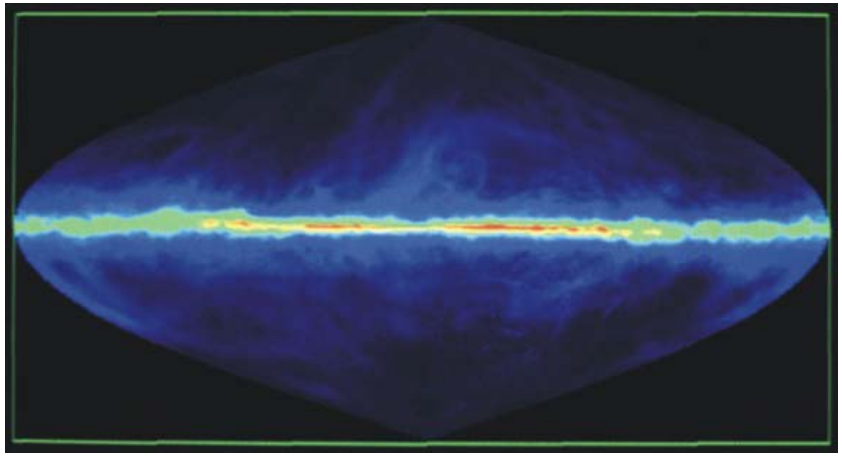
http://www.telemuseum.se/historia/mobtel/mobtfn_2e.html

Not long ago…

Now…



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