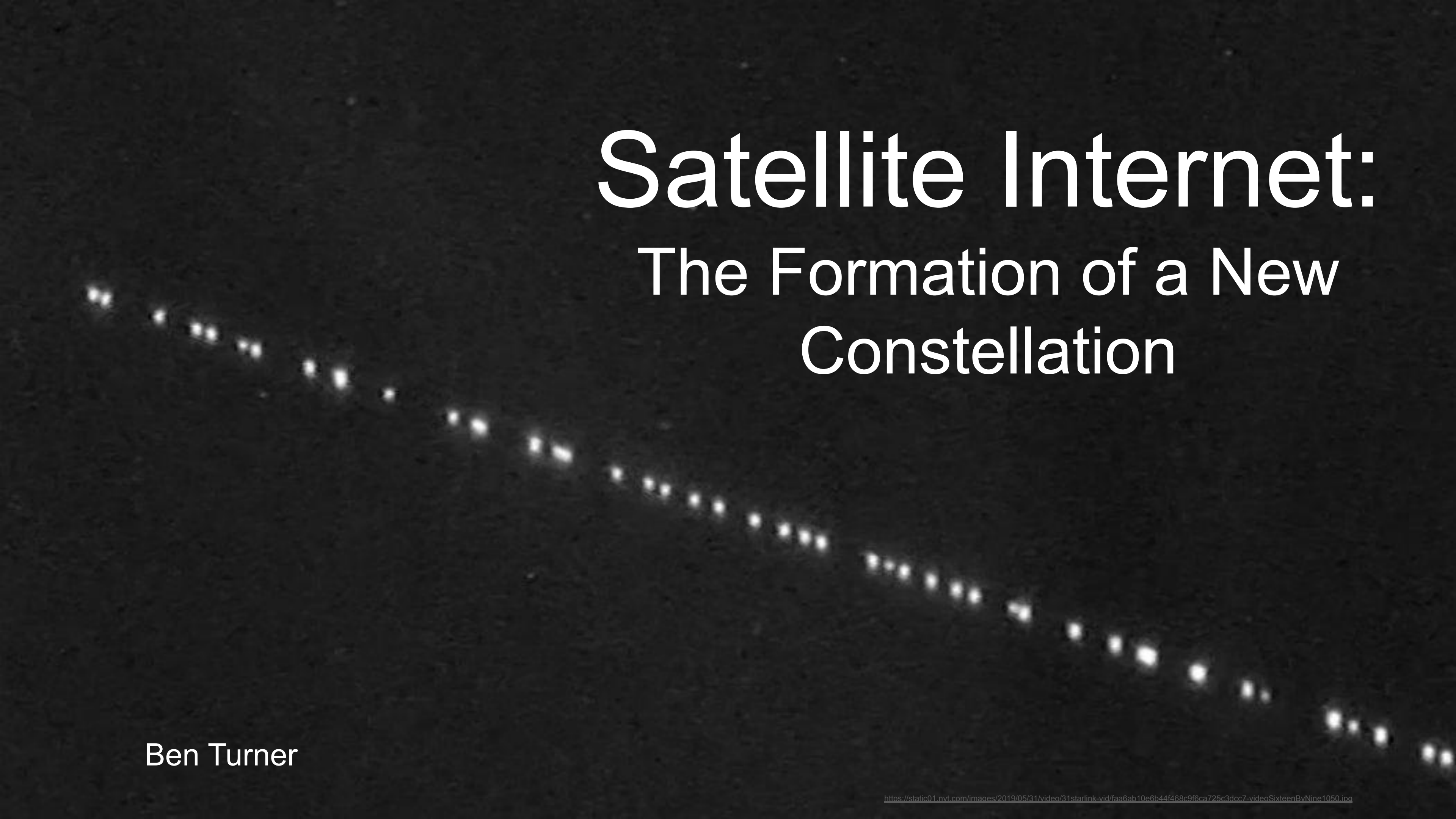

Satellite Internet:

The Formation of a New Constellation

Ben Turner

https://static01.nyt.com/images/2019/05/31/video/31starlink-vid/faa6ab10e6b44f468c9f6ca725c3dcc7-videoSixteenByNine1050.jpg

Acknowledgements

- Family
- Friends
- Peers
  - Kanishk
  - Osip
- Professors
  - Marty
  - Ryan
- Everyone who is here!

https://www.gannett-cdn.com/presto/2020/04/17/USAT/7620a49d-39e9-4db9-a96c-89f3d1deb1ae-facebookreact2.png

★ = current section

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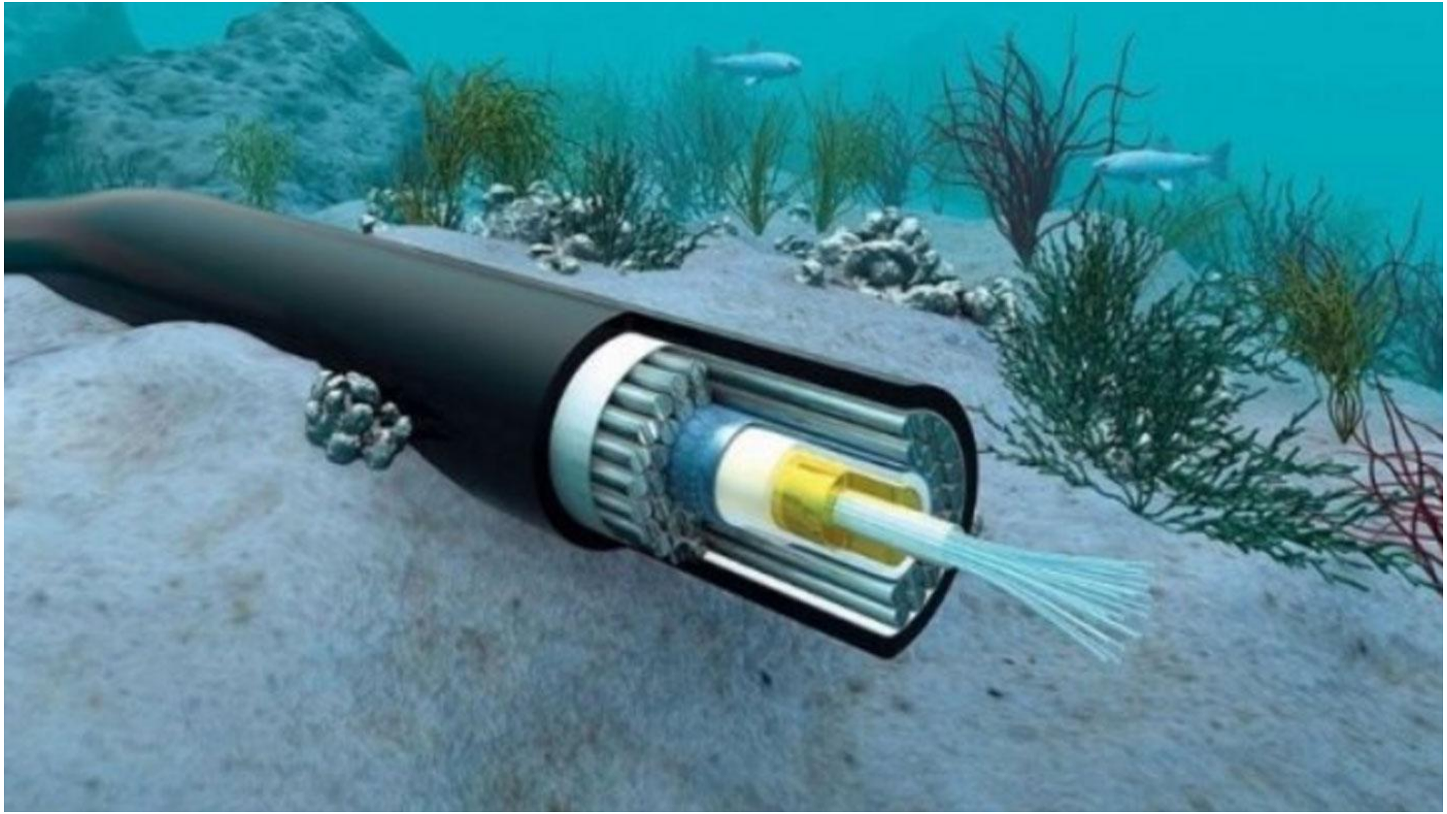
What the Internet seems like…

https://imageio.forbes.com/blogs-images/janakirammsv/files/2017/07/edge-computing.jpg?format=jpg&width=960

What it actually is…



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❶

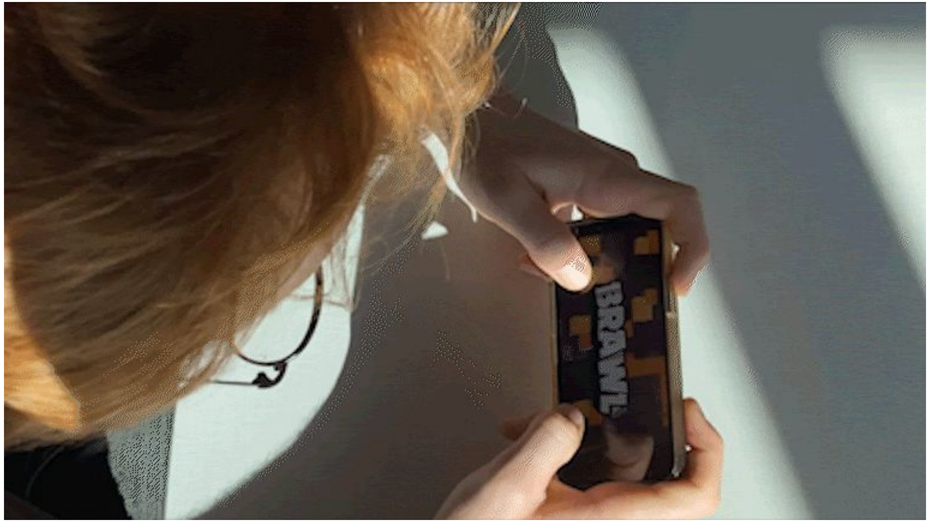
Brawl Stars!

RELEASE DATE
December 12, 2018

GENRE
MOBA

DEVELOPER
Supercell

PUBLISHER
Supercell



1

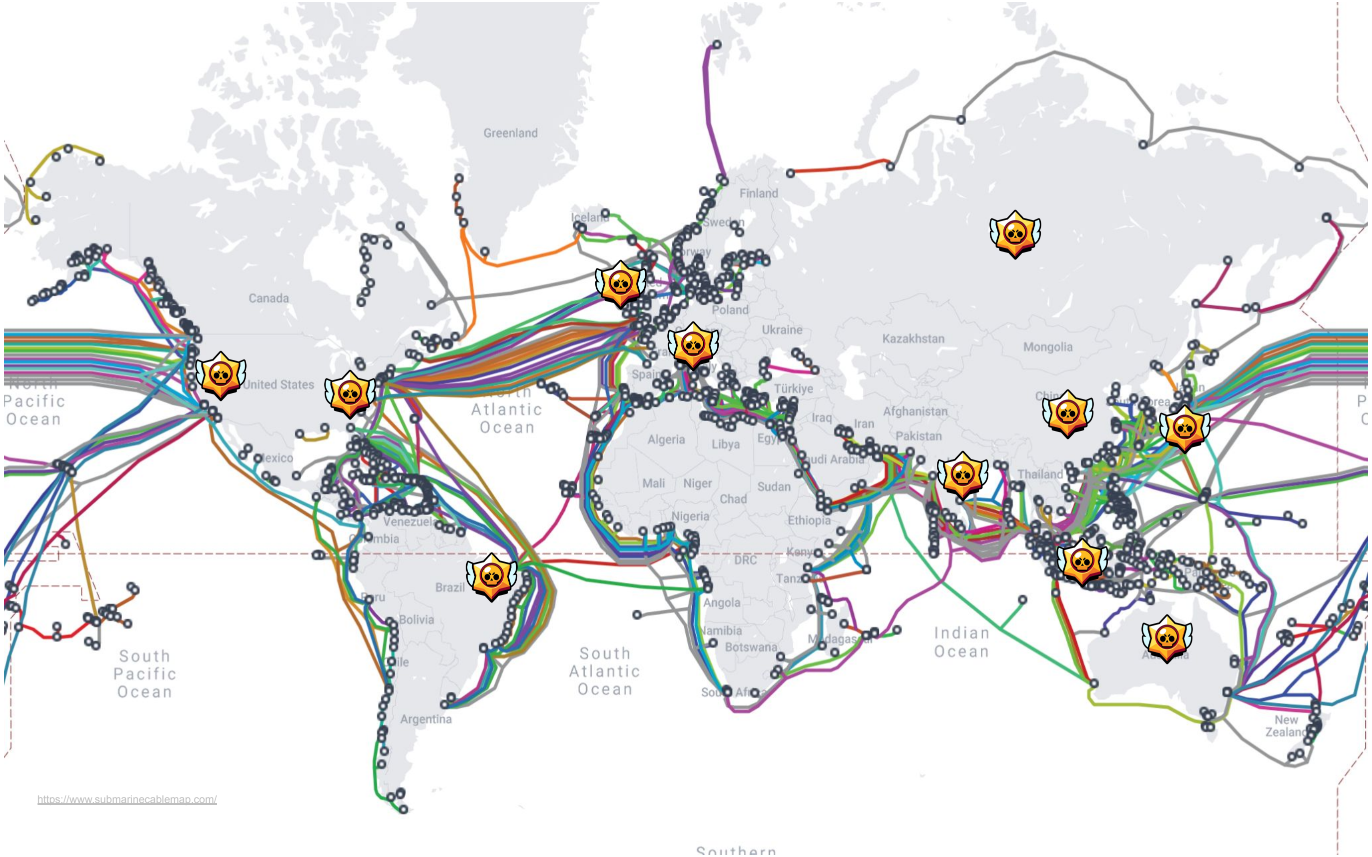
Internet Structure

Key Terms:

- Internet
- Signal
- Latency (Ping)
- Bandwidth

https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.webfx.com%2Fblog%2Finternet%2Fthe-structure-of-the-internet-infographic%2F&psig=AOvVaw3ktAbmqquHrLc_S85mPuDo&ust=1676071876754000&source=images&cd=vfe&ved=0CA8QjRxqFwoTCNi5gLnMif0CFQAAAAAdAAAAABAD

Wired Internet



But…

37% of world is *not* connected

*as of 2021

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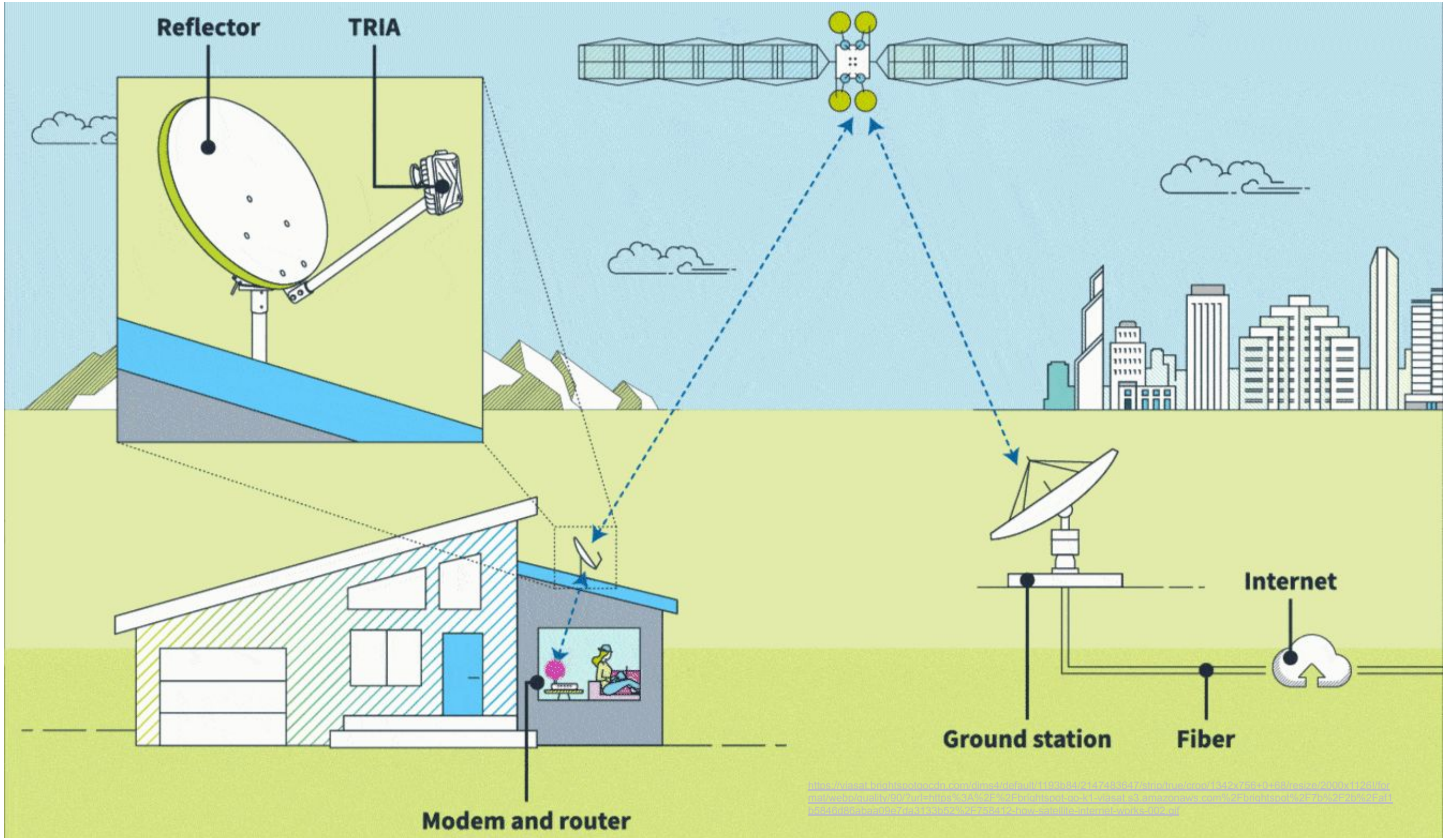
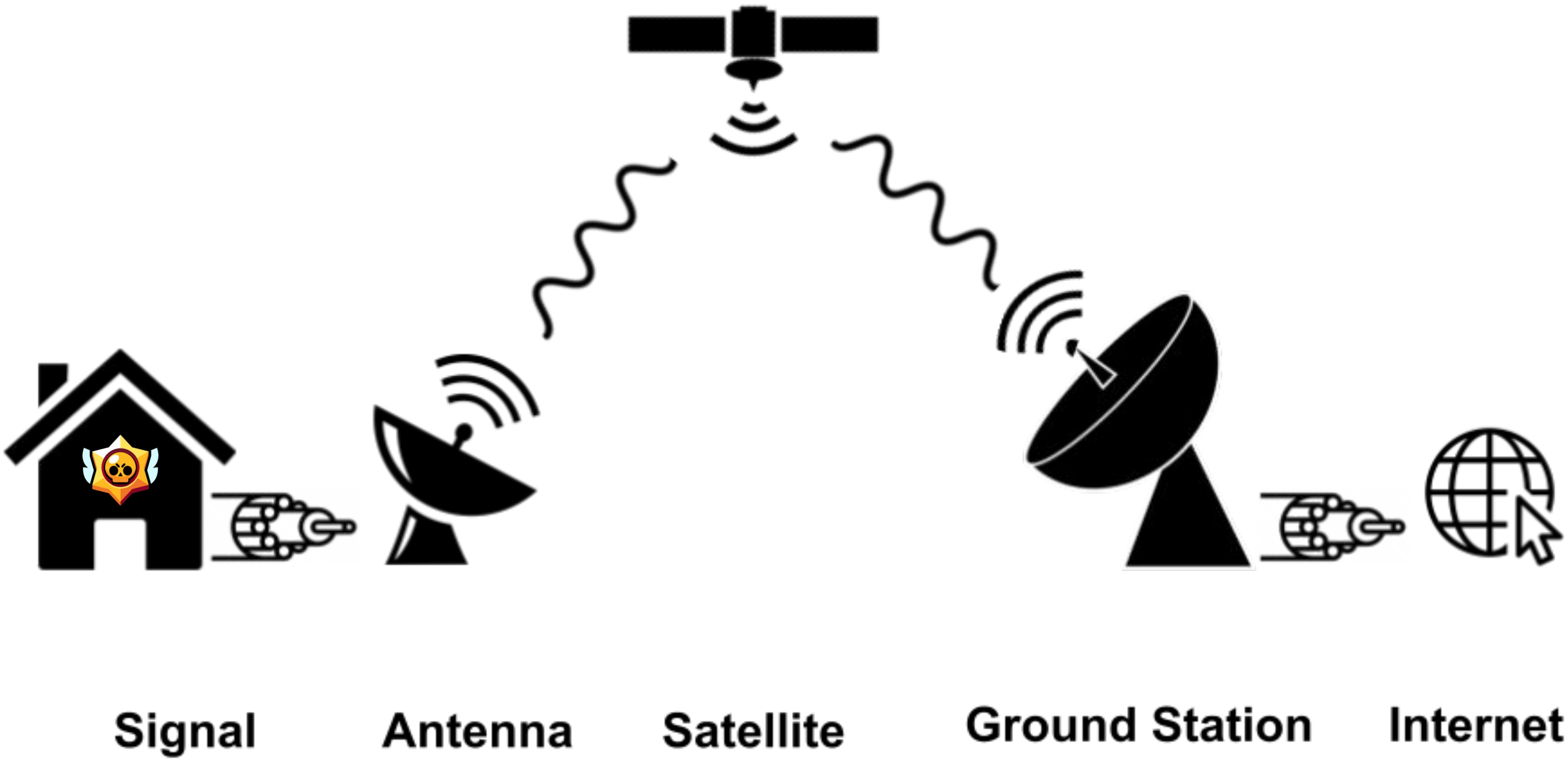
Components of a Satellite Internet System



https://viasat.brightspotgocdn.com/dims4/default/1193b84/2147483647/strip/true/crop/1342x756+0+68/resize/2000x1126!/format/webp/quality/90/?url=https%3A%2F%2Fbrightspot-go-k1-viasat.s3.amazonaws.com%2Fbrightspot%2F7b%2F2b%2Faf1b5846d86abaa09e7da3133b52%2F758412-how-satellite-internet-works-002.gif

❶

Satellite Communications System



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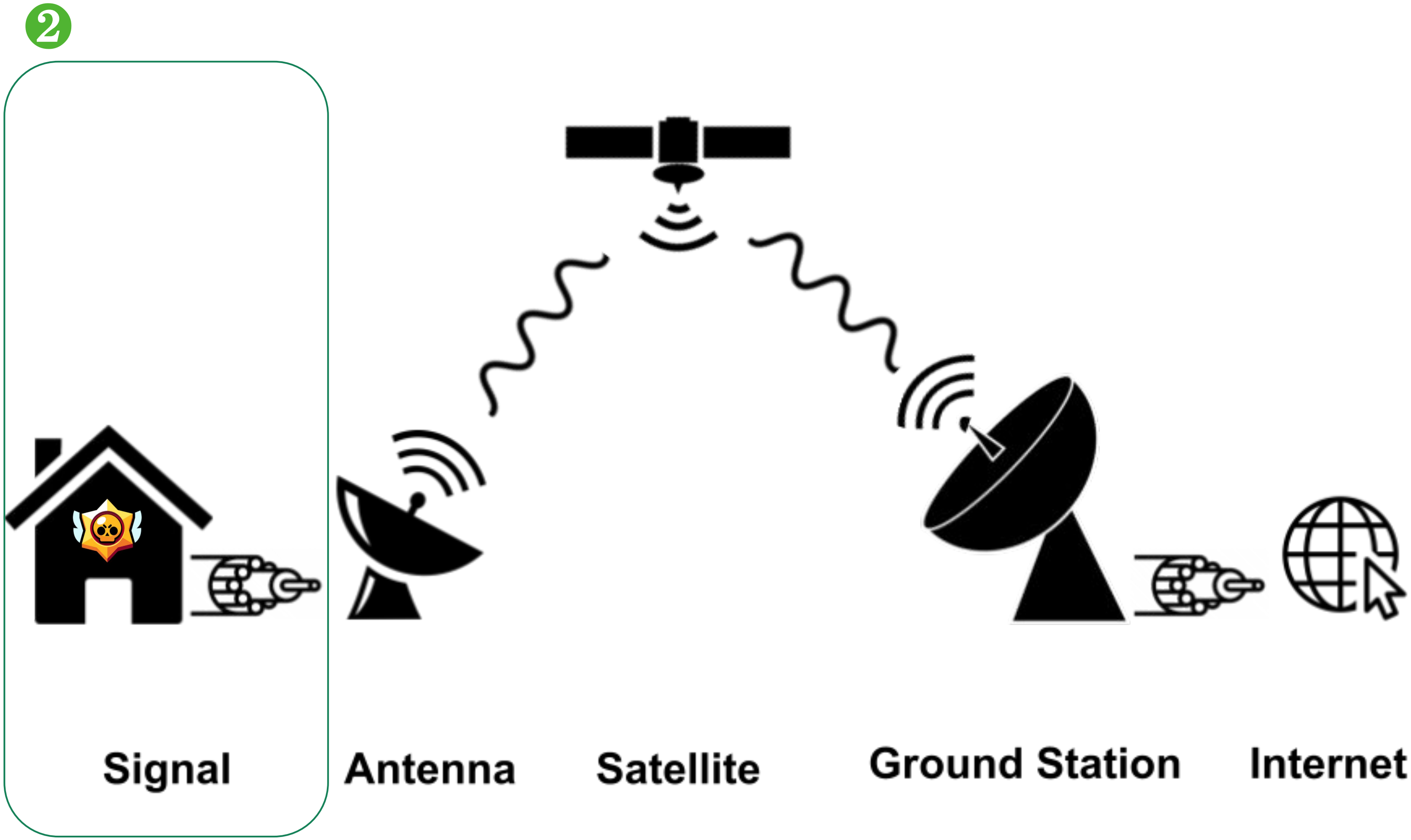
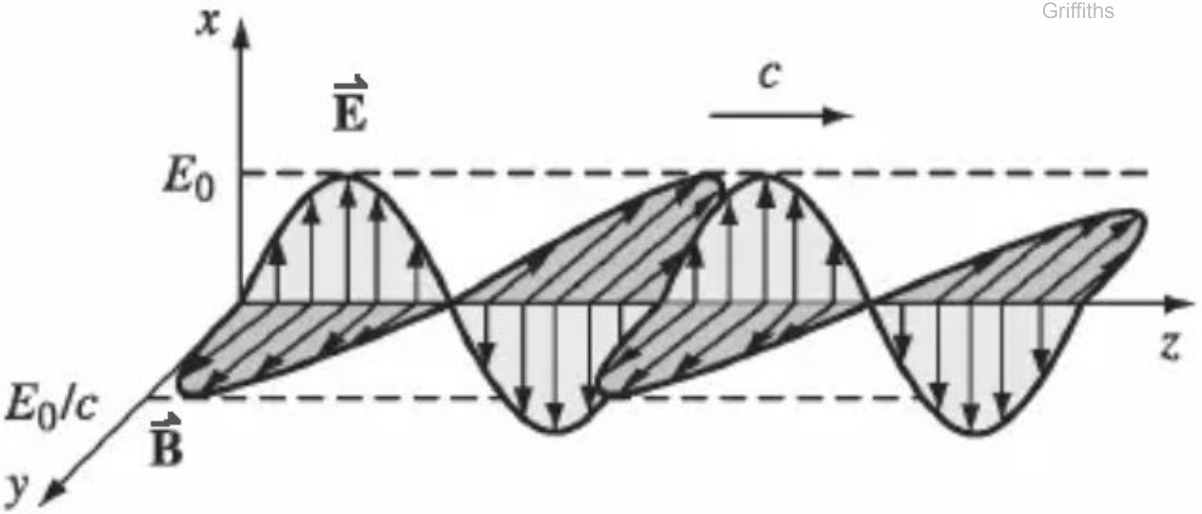

2
Signal
Antenna
Satellite
Ground Station
Internet

Griffiths

What is a signal?



Brawl Stars

- Connection requests
- Game state updates
- Input commands
- Chat messages

$$\vec{E}(\vec{r},t) = \boxed{E_0}\cos(\vec{k}\cdot\vec{r} - \boxed{\omega}t + \boxed{\phi_0})\hat{E}$$

$$\vec{B}(\vec{r},t) = \boxed{B_0}\cos(\vec{k}\cdot\vec{r} - \boxed{\omega}t + \boxed{\phi_0})\hat{B}$$

Signal = Data
bits (**0** or **1**)

Encode data in:
- amplitude
- phase
- angular frequency

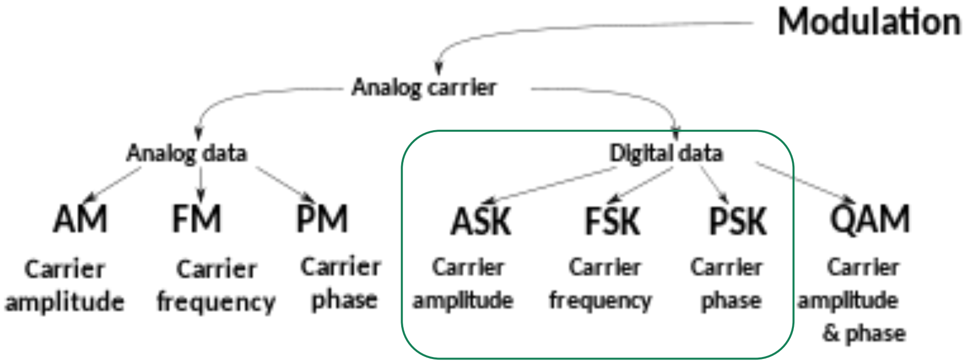
Signal Modulation

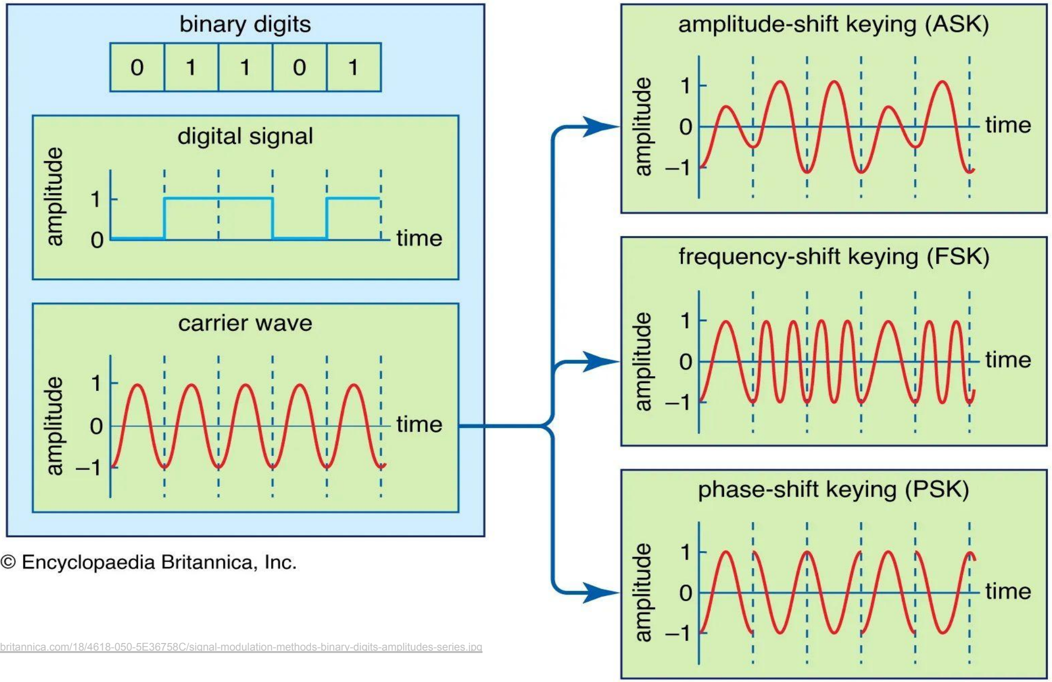
$$\vec{E}(\vec{r},t) = \boxed{E_0}\cos(\vec{k}\cdot\vec{r} - \boxed{\omega t} + \boxed{\phi_0})\hat{E}$$

amplitude

angular frequency

phase



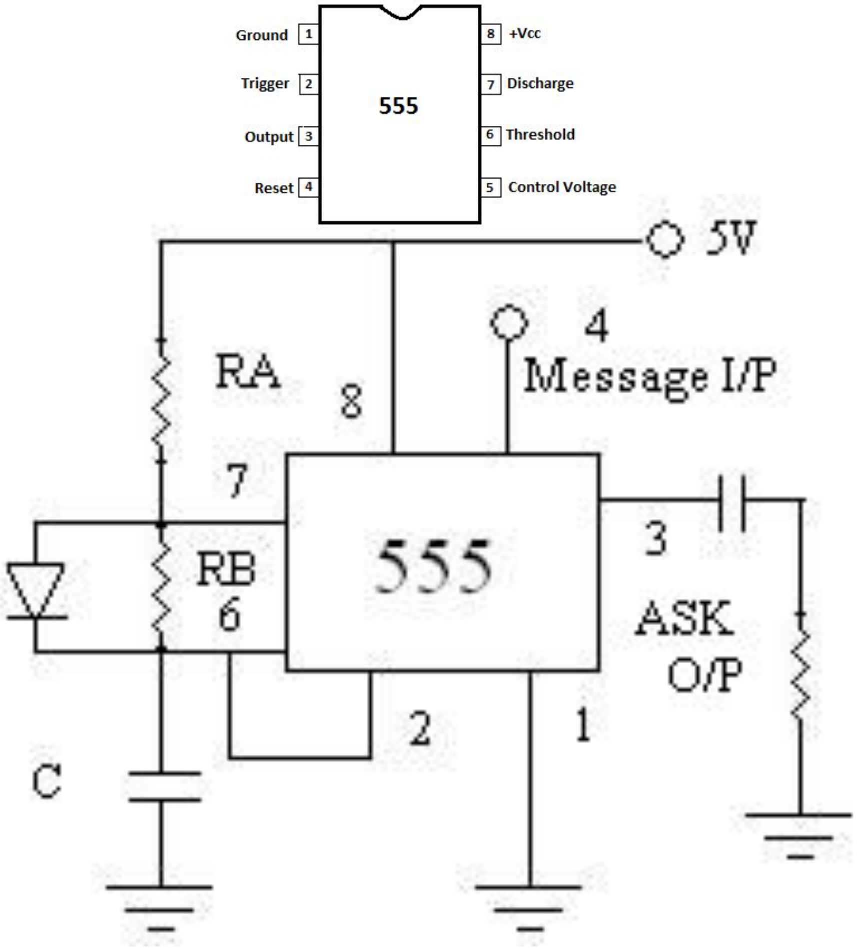


https://upload.wikimedia.org/wikipedia/commons/thumb/e/e7/Modulation_categorization.svg/1599px-Modulation_categorization.svg.png

https://cdn.britannica.com/18/4618-050-5E36758C/signal-modulation-methods-binary-digits-amplitudes-series.jpg

❷

A closer look: ASK Circuit



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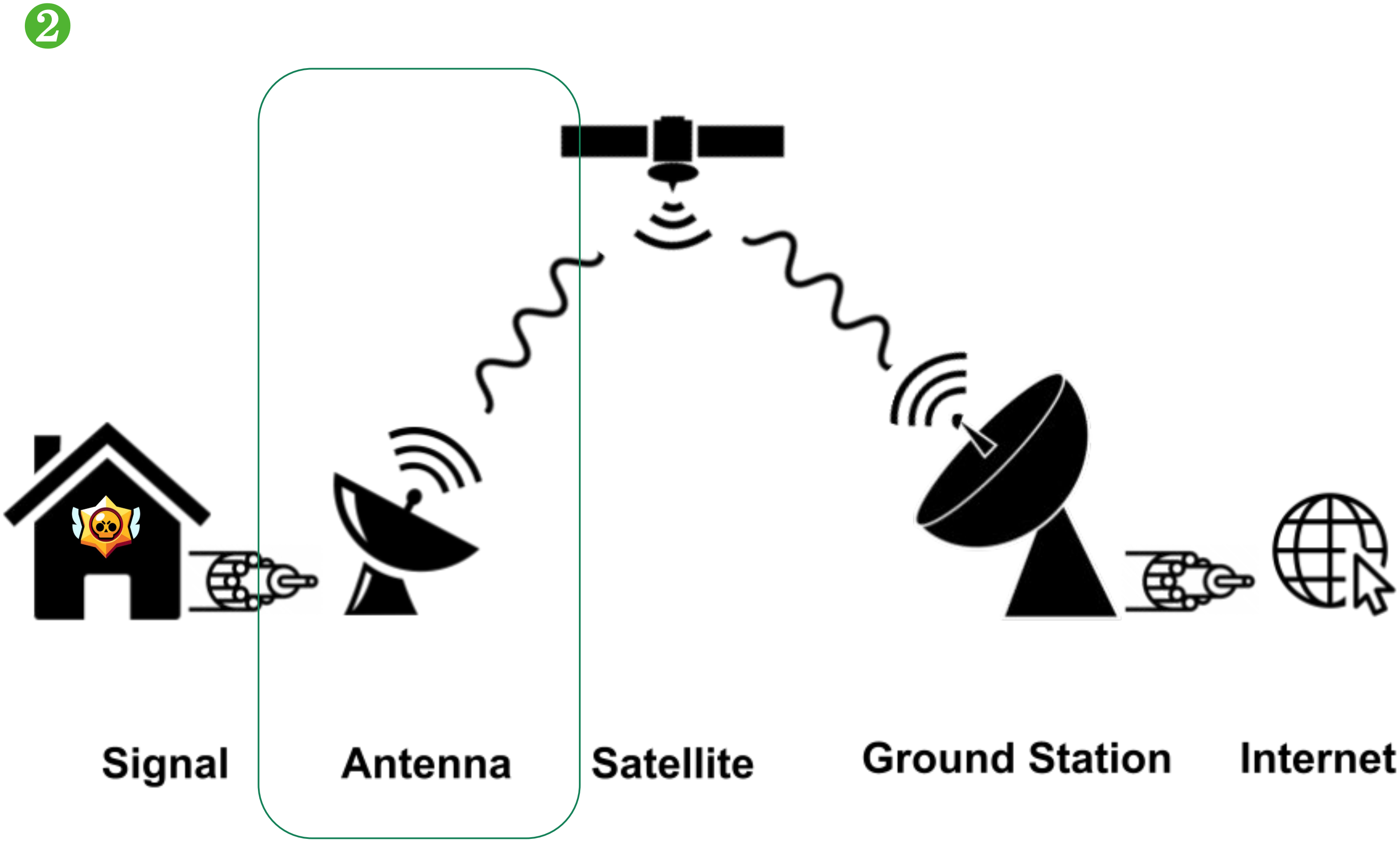


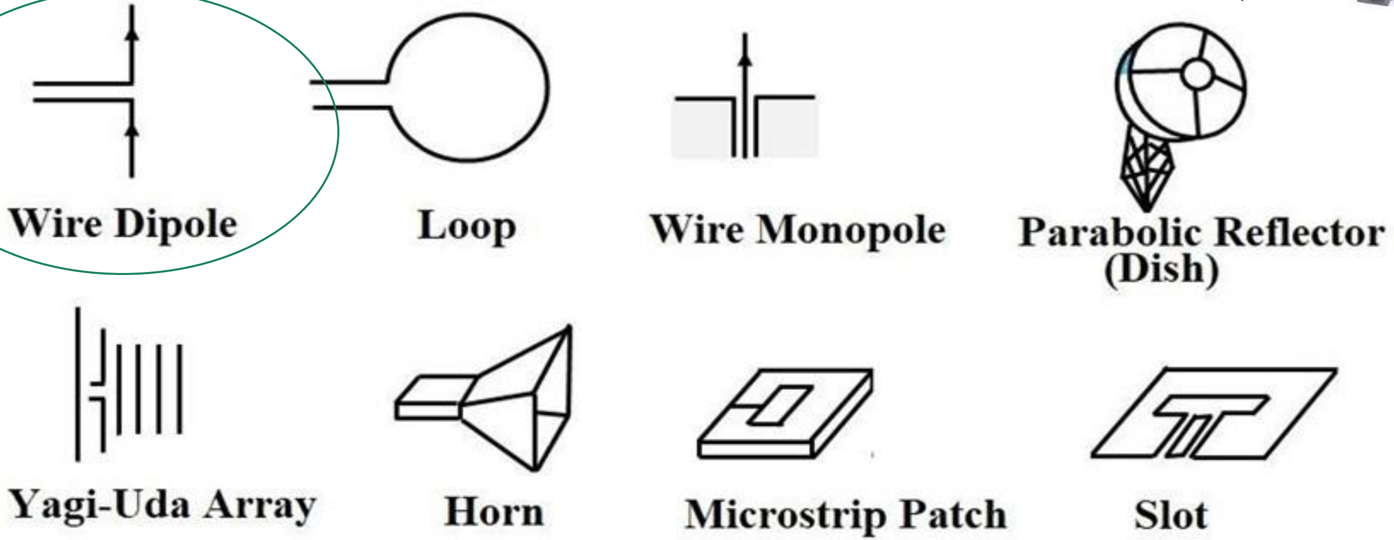
2
Signal
Antenna
Satellite
Ground Station
Internet

2

Reflector

TRIA

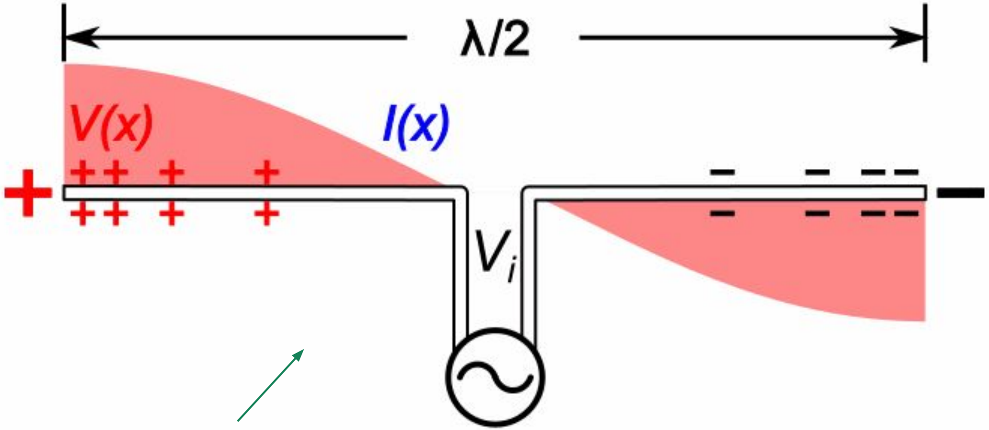
What are Antennas?



https://www.researchgate.net/profile/Manpreet-Dhillon-4/publication/322509437/figure/fig15/AS:668599723229224@1536418004899/Several-types-of-Antennas-6.jpg

❷

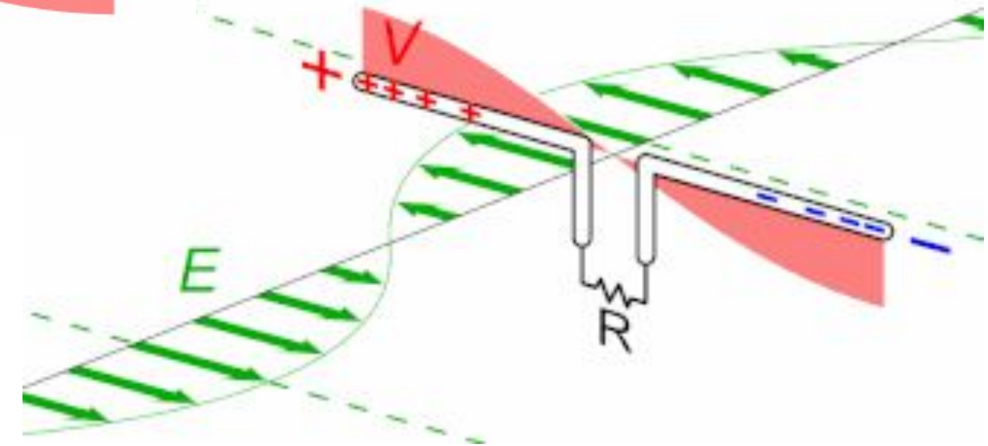
Visualizing a Dipole Antenna



Transmitting

https://upload.wikimedia.org/wikipedia/commons/f/fe/Dipole_antenna_standing_waves_animation_6_-_5fps.gif

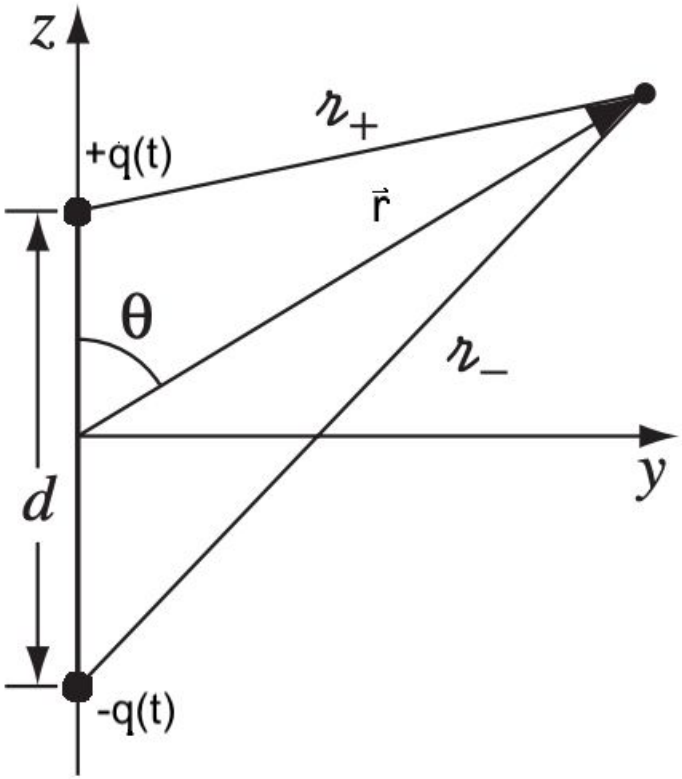
Receiving



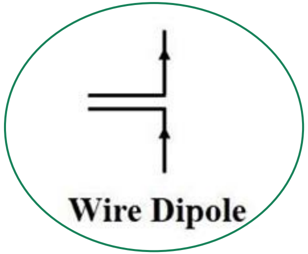
https://upload.wikimedia.org/wikipedia/commons/thumb/d/dd/Dipole_receiving_antenna_animation_6_800x394x150ms.gif/330px-Dipole_receiving_antenna_animation_6_800x394x150ms.gif

❷

Deriving the Electric Field



Griffiths



Charge

$$q(t) = q_0 \cos(\omega t)$$

Electric dipole

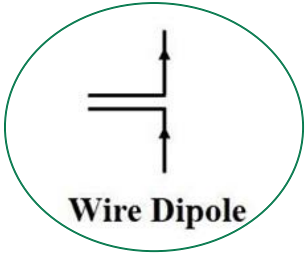
$$\vec{p}(t) = p_0 \cos(\omega t)\hat{z}$$

Max dipole moment

$$p_0 \equiv q_0 d$$

❷

Maxwell's Equations



Given

$$\rho(\vec{r}, t)$$

$$\vec{J}(\vec{r}, t)$$

what are $\vec{E}$ and $\vec{B}$?

We define $\vec{A}$ as

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

(1) $$\vec{\nabla} \cdot \vec{E} = \frac{1}{\epsilon_0}\rho$$

(2) $$\vec{\nabla} \cdot \vec{B} = 0$$

Gauss' Laws

(3) $$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Faraday's Law

(4) $$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

Ampere's Law

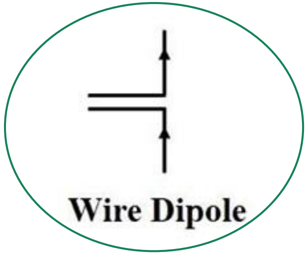
In terms of potentials:

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\vec{E} = -\vec{\nabla} V - \frac{\partial \vec{A}}{\partial t}$$

❷

Potential representations



$$\vec{E} = -\vec{\nabla} V - \frac{\partial \vec{A}}{\partial t}$$

into **Eq. (1)**

$$\nabla^2 V + \frac{\partial}{\partial t}(\nabla \cdot A) = -\frac{1}{\epsilon_0}\rho$$

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\vec{E} = -\vec{\nabla} V - \frac{\partial \vec{A}}{\partial t}$$

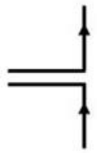
into **Eq. (4)**

$$\left(\nabla^2 \vec{A} - \mu_0\epsilon_0 \frac{\partial^2 \vec{A}}{\partial t^2}\right) - \vec{\nabla}\left(\vec{\nabla} \cdot \vec{A} + \mu_0\epsilon_0 \frac{\partial V}{\partial t}\right) = -\mu_0 \vec{J}$$

❷

Lorenz Gauge

$$\boxed{\vec{\nabla}\cdot\vec{A} = -\mu_0\epsilon_0\frac{\partial V}{\partial t}}$$



Wire Dipole

$$\nabla^2 V + \frac{\partial}{\partial t}(\nabla\cdot A) = -\frac{1}{\epsilon_0}\rho$$

$$\nabla^2 V + \mu_0\epsilon_0\frac{\partial^2 V}{\partial t^2} = -\frac{1}{\epsilon_0}\rho$$

$$\Box^2 V = -\frac{1}{\epsilon_0}\rho$$

$$\left(\nabla^2\vec{A} - \mu_0\epsilon_0\frac{\partial^2\vec{A}}{\partial t^2}\right) - \vec{\nabla}\cancelto{0}{\left(\vec{\nabla}\cdot\vec{A} + \mu_0\epsilon_0\frac{\partial V}{\partial t}\right)} = -\mu_0\vec{J}$$

$$\nabla^2\vec{A} - \mu_0\epsilon_0\frac{\partial^2\vec{A}}{\partial t^2} = -\mu_0\vec{J}$$

$$\Box^2\vec{A} = -\mu_0\vec{J}$$

In static case, these reduce to:

$$\nabla^2 V = -\frac{1}{\epsilon_0}\rho \qquad \nabla^2\vec{A} = -\mu_0\vec{J}$$

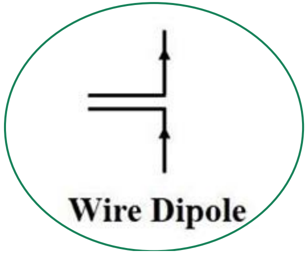
with solutions…

d’Alembertian

$$\Box^2 \equiv \nabla^2 - \mu_0\epsilon_0\frac{\partial^2}{\partial t^2}$$

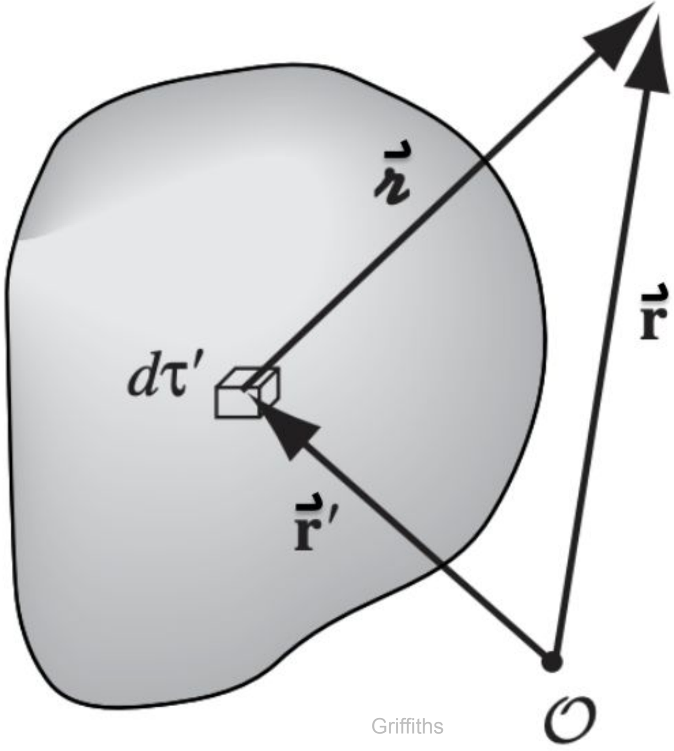
Retarded Time and Potential

$$t_r = t - \frac{\mathscr{r}}{c}$$



$$V(\vec{r}, t) = \frac{1}{4\pi\epsilon_0} \int \frac{\rho\left(\vec{r}\,', t_r\right)}{\vec{\mathscr{r}}} d\tau'$$

$$\vec{A}(\vec{r}, t) = \frac{\mu_0}{4\pi} \int \frac{\vec{J}\left(\vec{r}\,', t_r\right)}{\vec{\mathscr{r}}} d\tau'$$



These satisfy both

$$\vec{\nabla} \cdot \vec{A} = -\mu_0 \epsilon_0 \frac{\partial V}{\partial t}$$

and

$$\Box^2 V = -\frac{1}{\epsilon_0}\rho$$

$$\Box^2 \vec{A} = -\mu_0 \vec{J}$$

❷

Scalar Potential

$$V(\vec{r},t) = \frac{1}{4\pi\epsilon_0}\left\{\frac{q_0\cos\left[\omega(t - {}_{+}/c)\right]}{\mathscr{r}_+} - \frac{q_0\cos\left[\omega(t - {}_{-}/c)\right]}{\mathscr{r}_-}\right\}$$

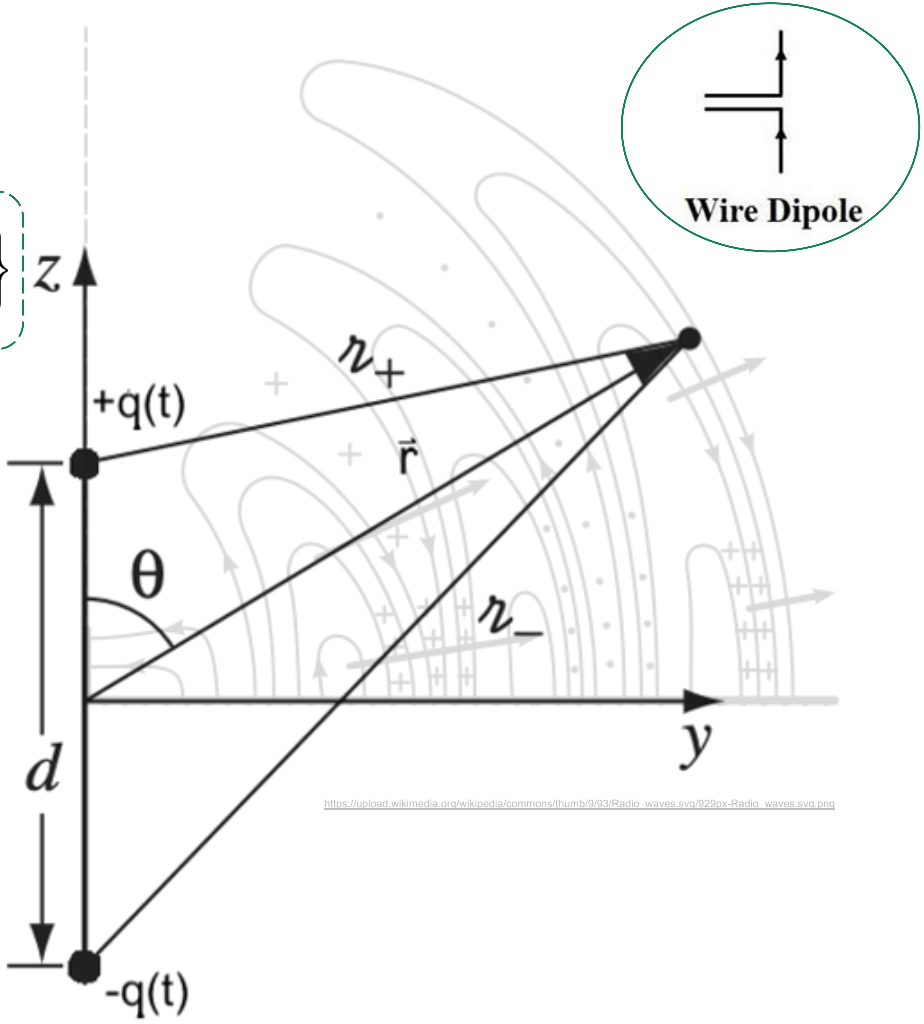
Approximation 1: $d \ll r$

Approximation 2: $d \ll \lambda$

$\lambda = \frac{c}{\omega}$

Approximation 3: $r \gg \lambda$

$$V(r,\theta,t) = -\frac{p_0\omega}{4\pi\epsilon_0 c}\left(\frac{\cos\theta}{r}\right)\sin\left[\omega(t - r/c)\right]$$



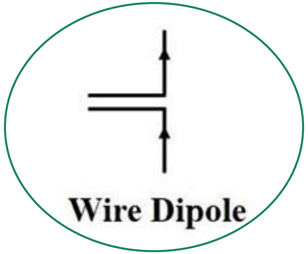
❷

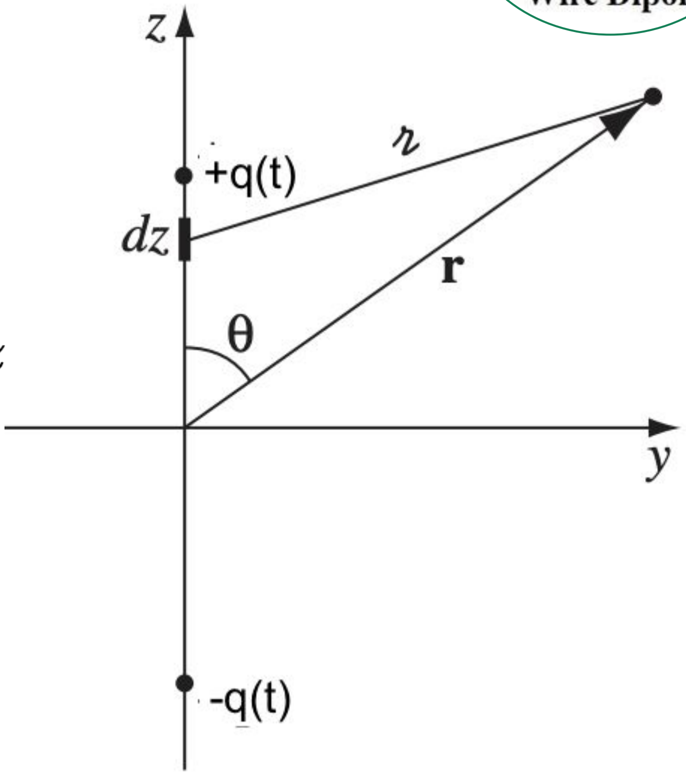
Vector Potential

$$\vec{I}(t) = \frac{\mathrm{d}q}{\mathrm{d}t}\hat{z} = -q_0\omega\sin(\omega t)\hat{z}$$

$$\vec{A}(\vec{r},t) = \frac{\mu_0}{4\pi}\int_{-d/2}^{d/2}\frac{-q_0\omega\sin[\omega(t - \quad /c)]\hat{z}}{\mathscr{r}}dz$$

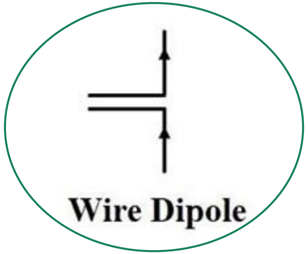
$$\boxed{\vec{A}(r,\theta,t) = -\frac{\mu_0 p_o\omega}{4\pi r}\sin[\omega(t - r/c)]\hat{z}}$$





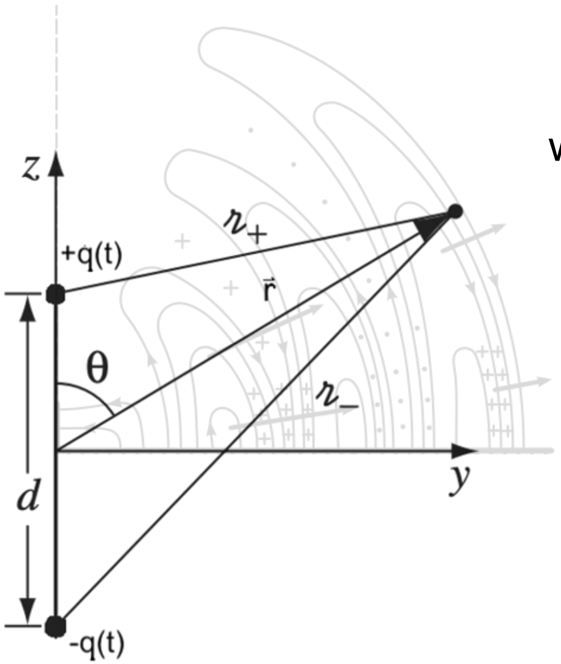
❷

The Electromagnetic Fields of a Dipole Antenna



From

$$\vec{E} = -\vec{\nabla}V - \frac{\partial \vec{A}}{\partial t} \qquad \vec{B} = \vec{\nabla} \times \vec{A}$$



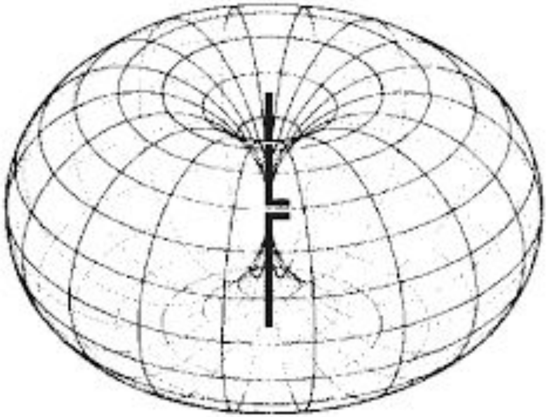
we get

$$\vec{E} = -\frac{\mu_0 p_0 \omega^2}{4\pi}\left(\frac{\sin\theta}{r}\right)\cos[\omega(t - r/c)]\hat{\theta}$$

$$\vec{B} = -\frac{\mu_0 p_0 \omega^2}{4\pi c}\left(\frac{\sin\theta}{r}\right)\cos[\omega(t - r/c)]\hat{\phi}$$

❷

Antenna Properties



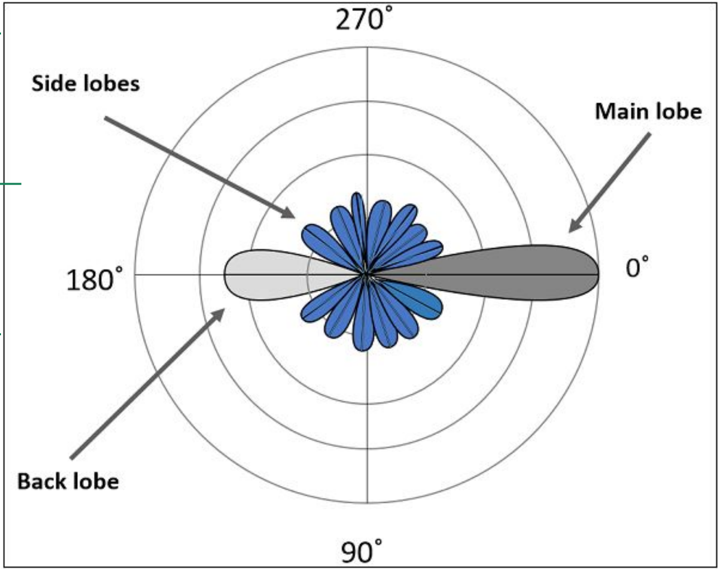
- Poynting Vector $\vec{S}(\vec{r},t) = \frac{1}{\mu_0}\left(\vec{E}\times\vec{B}\right)$

- Radiation Intensity $U(\theta,\phi) = r^2\langle S\rangle = (\frac{\mu_0 p_0^2\omega^4}{32\pi^2 c})\sin^2\theta$

- Power $P_{rad} = \oint\langle\vec{S}\rangle\cdot d\vec{a} = \frac{\mu_0 p_0^2\omega^4}{12\pi c}$

- Directivity $D(\theta,\phi) = 4\pi\frac{U(\theta,\phi)}{P_{rad}} = \frac{3}{2}\sin^2\theta$

- Gain $G(\theta,\phi) = \eta_{rad}D(\theta,\phi) = \eta_{rad}\frac{3}{2}\sin^2\theta$



https://www.tutorialspoint.com/antenna_theory/images/omni_directional_radiation.jpg https://www.tutorialspoint.com/antenna_theory/images/lobe_formation.jpg

Osip before his comps

Me before my comps

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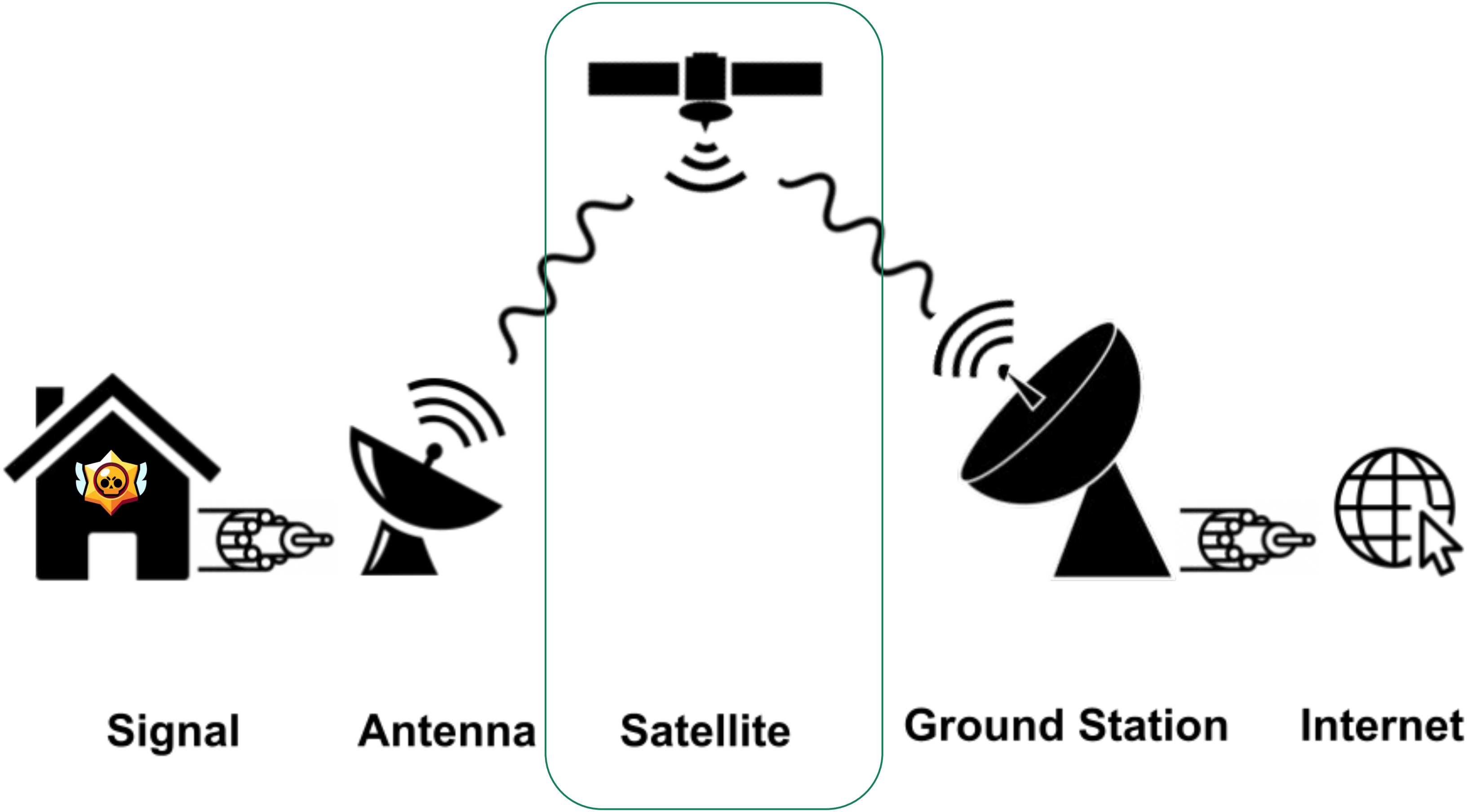
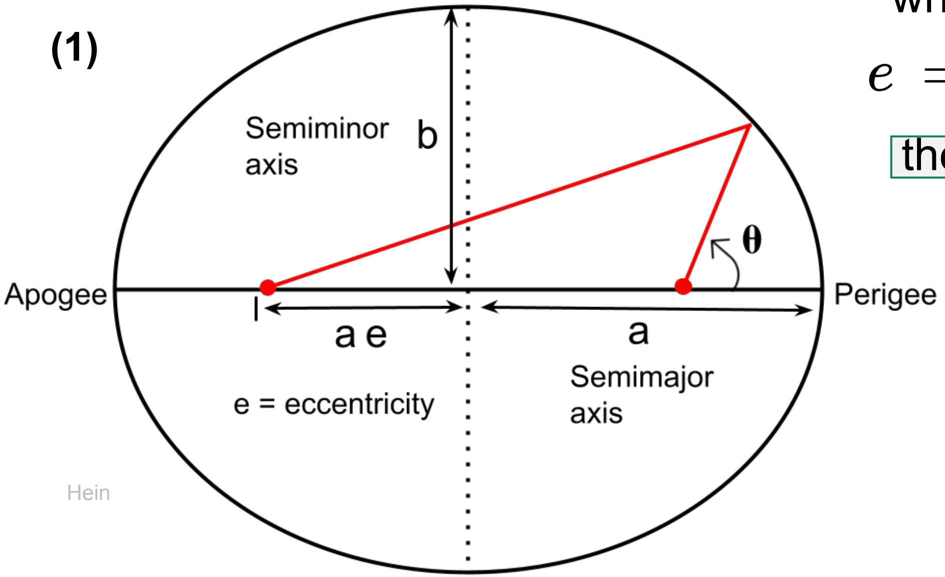


❷

Kepler's Laws of Planetary Motion

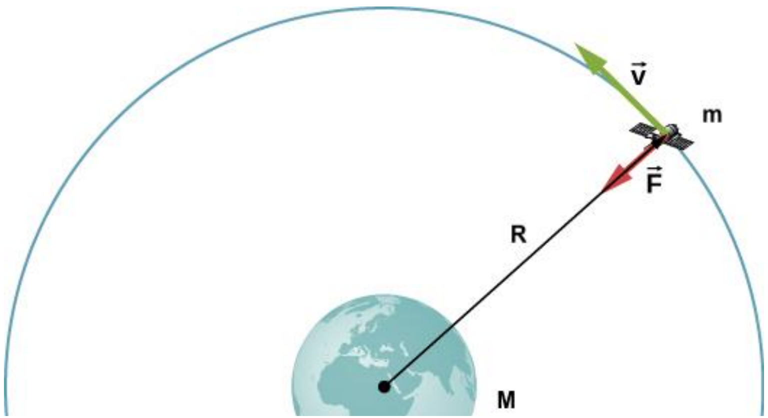
(1)



when

$$e = 0$$

then



https://s3-us-west-2.amazonaws.com/courses-images/wp-content/uploads/sites/2952/2018/01/31200003/CNX_UPhysics_13_04_orbit.jpg

Most telecommunications satellites are in **quasi-circular** orbits.

$$F_g = \frac{GMm}{R^2} = \frac{mv^2}{R} = F_c$$

$$v = \sqrt{\frac{GM}{R}} \qquad T^2 = \frac{4\pi^2}{GM} R^3$$

(3)

$$T^2 = \frac{4\pi^2}{GM} a^3$$

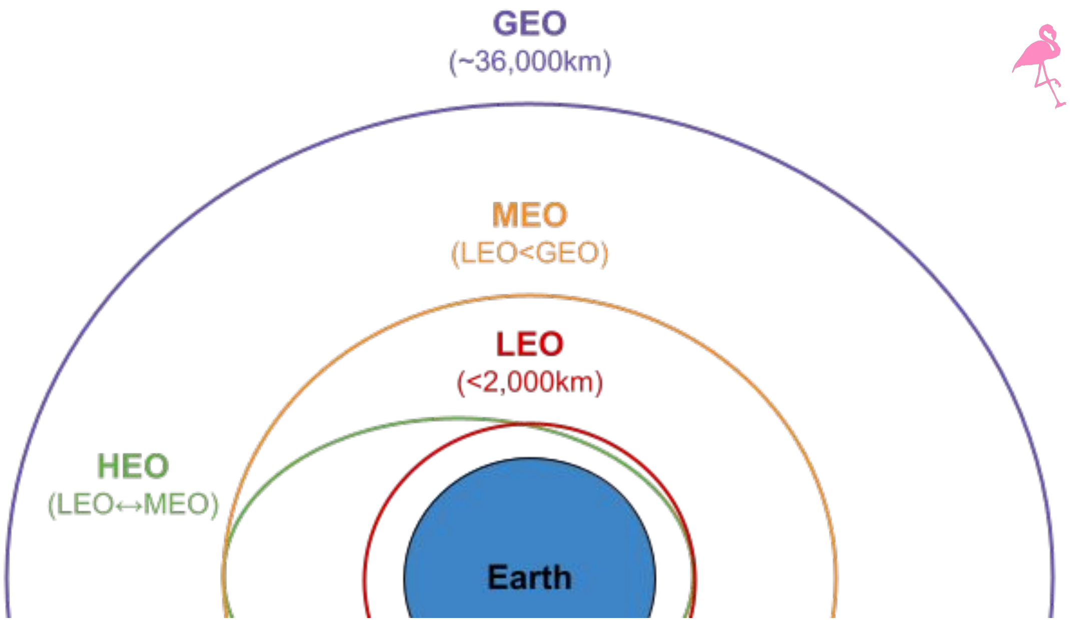
❷

Types of Orbits

We will focus on

- **LEO** (Low Earth Orbit)
  200 km < 2000 km

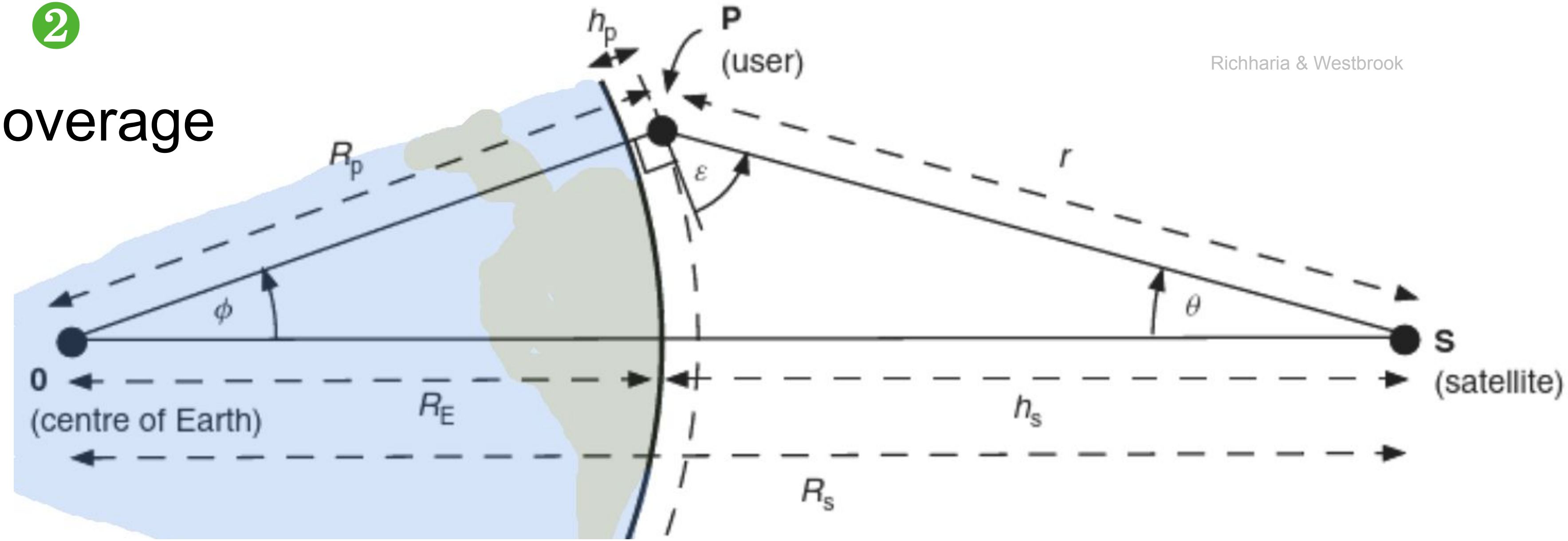
- **GEO** (Geostationary Earth Orbit)
  ≈ 36000 km



Orbit	Altitude (km)	Period	Velocity	$\theta°$	$\psi°$	Coverage radius (km)	Coverage Area (km^2)	Fractional coverage (%)
HAP	20	–	–	79.0	0.97	108	36 563	0.0072
LEO	800	1 h 40 min	7450 m/s	61.0	19.0	2106	1.38×10^7	2.7
MEO	20 000	11 h 50 min	3887 m/s	13.7	66.3	7351	1.52×10^8	29
GEO	35 786	23 h 56′ 4.09″	3 074.7 m/s	8.54	71.5	7928	1.73×10^8	34

❷

Coverage



$$\theta = \sin^{-1}\left(\frac{R_p}{R_S}\cos\epsilon\right)$$

$$\phi = \frac{\pi}{2} - \theta - \epsilon$$

$$\Omega_C = 2\pi(1 - \cos\phi)$$

$$\boxed{A_C = \Omega_C R_E^2}$$

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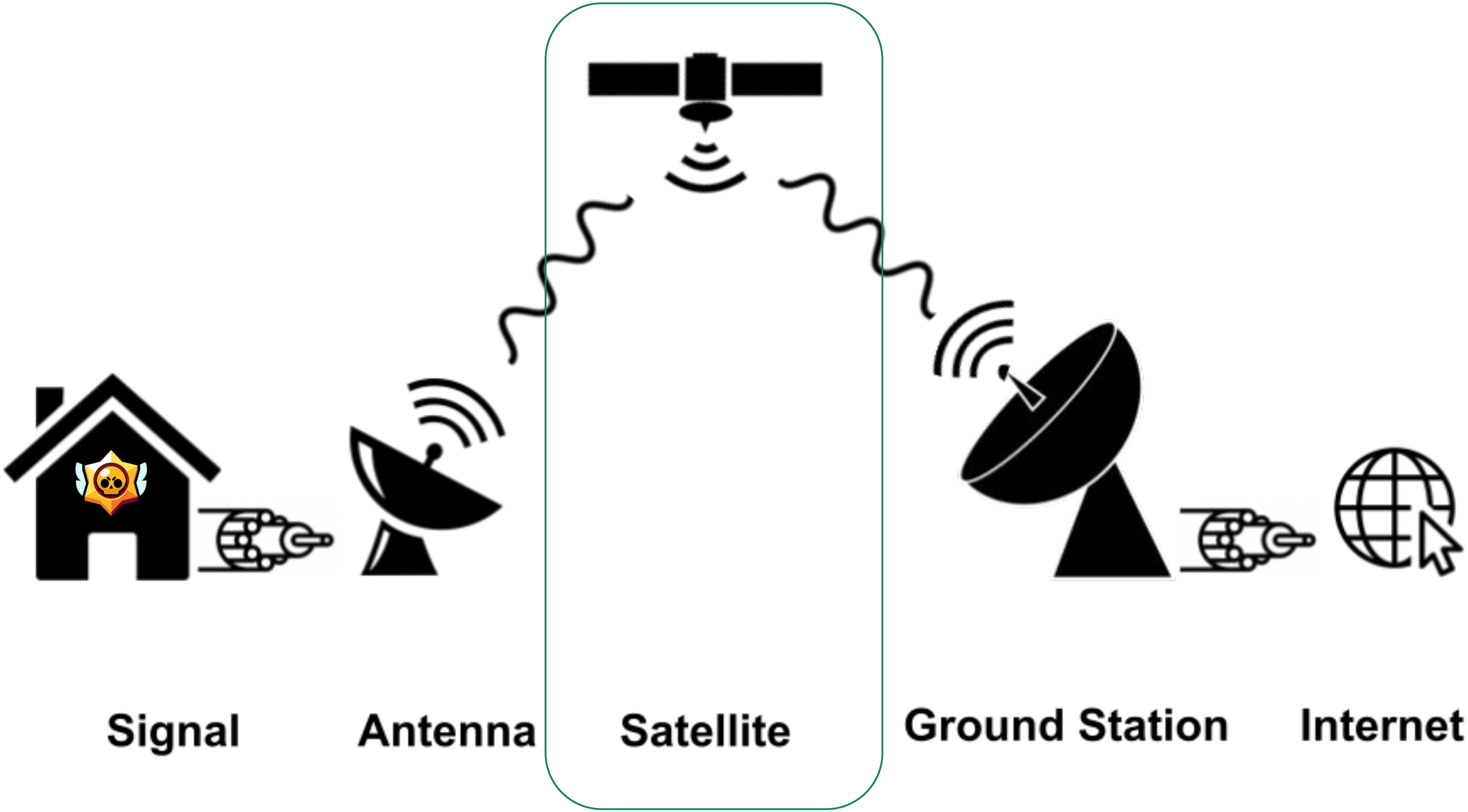
   - Pros and Cons of Starlink

❷



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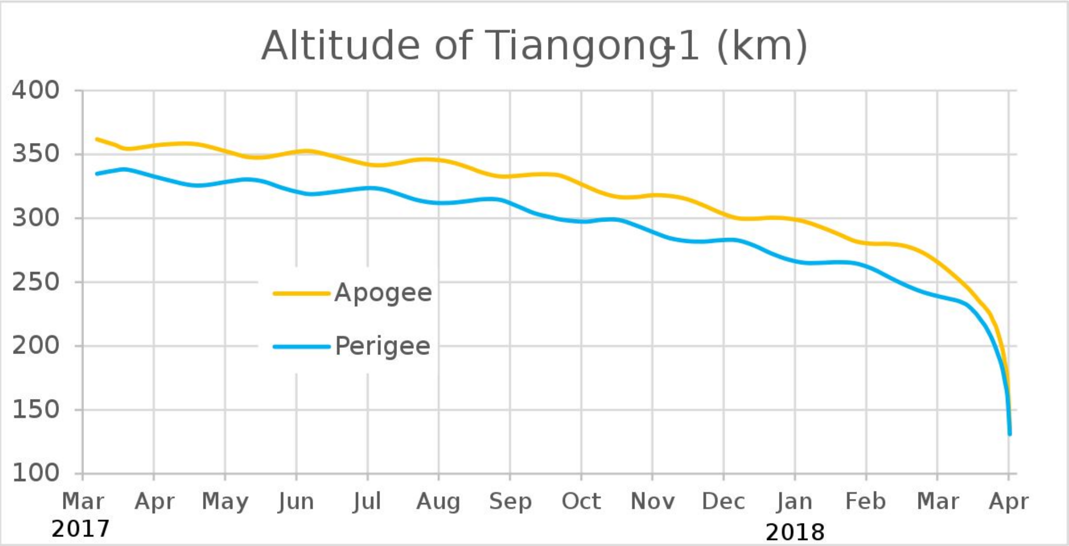
Satellite Orbital Decay

- Gravitational forces
- Atmospheric Drag
- Tidal effects
- Light and thermal radiation



https://upload.wikimedia.org/wikipedia/commons/thumb/0/0e/Altitude_of_Tiangong-1.svg/580px-Altitude_of_Tiangong-1.svg.png

Simplified model

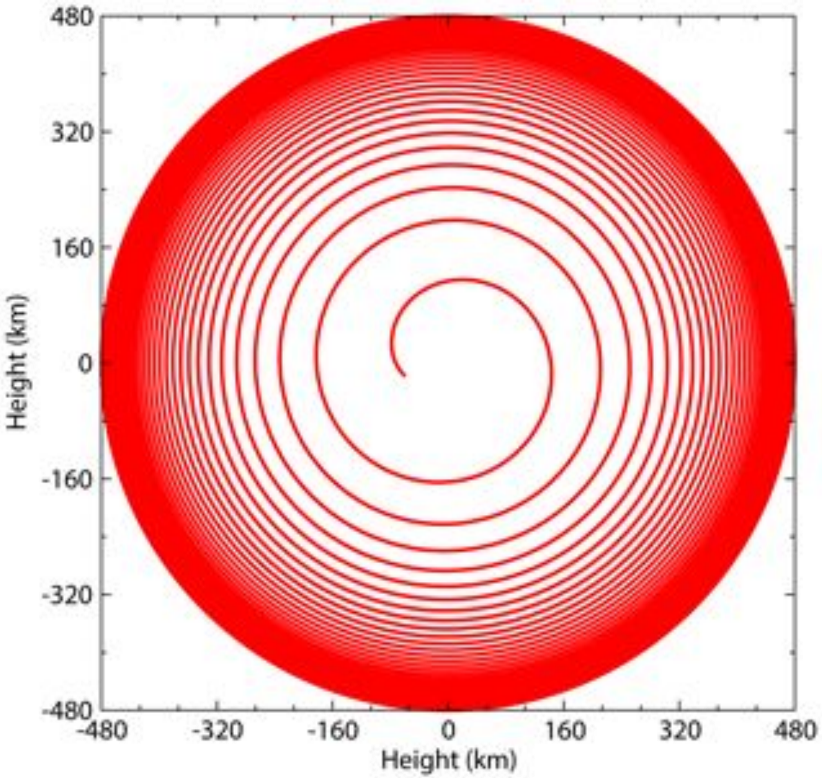
$$\frac{\mathrm{d}R}{\mathrm{d}t} = \frac{\alpha_o(R) \cdot T(R)}{\pi}$$

❷

Atmospheric Drag for LEO

200-400 km orbits face significant drag

$$\alpha_0(R) = \frac{1}{2}\rho(R)v^2 c_d \frac{A}{m}$$



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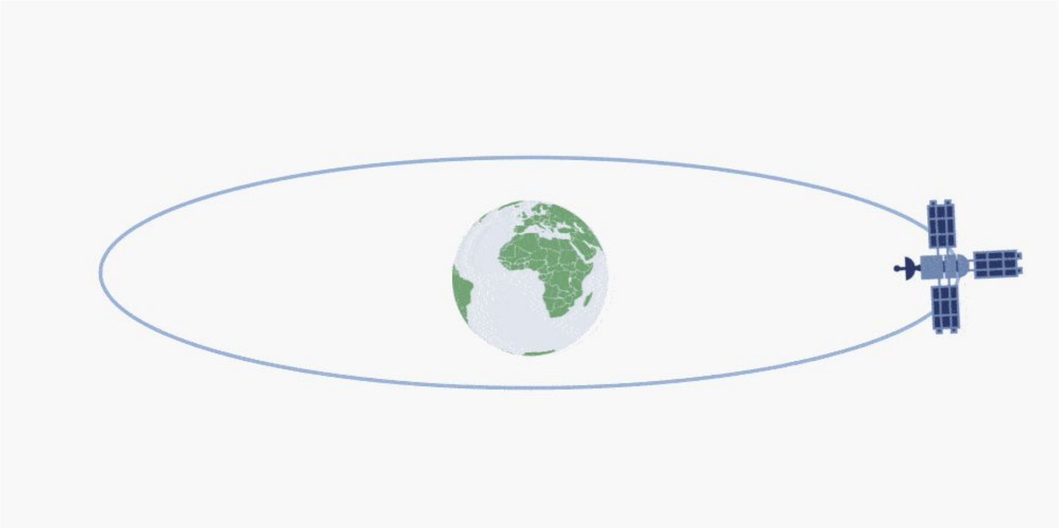
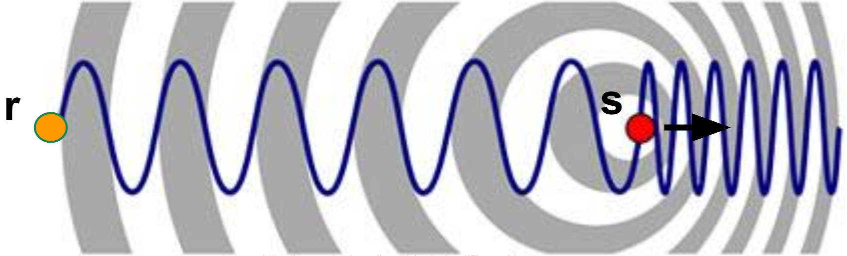
Locating and keeping a satellite in orbit

Combine techniques to *determine* satellite location in *time* and *space*

- Global Positioning System (GPS)
- Inertial Navigation Systems (INS)
- Star trackers
- Satellite laser ranging (SLR)
- **The Doppler effect**



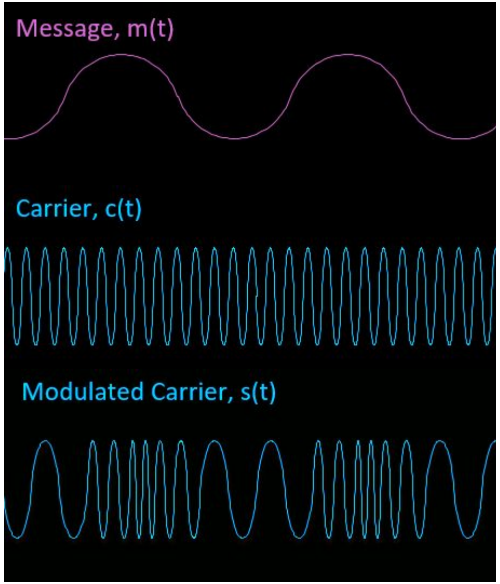
$$f = \left(\frac{c \pm v_r}{c \pm v_s}\right) f_0$$

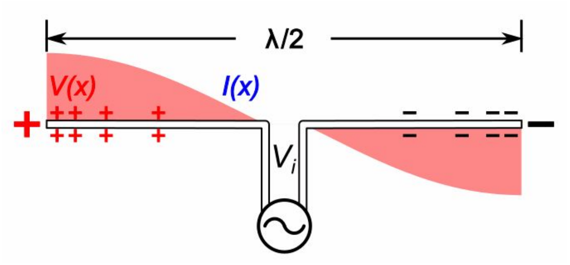


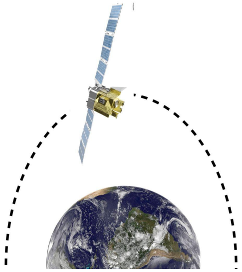
https://www.ontrack-media.net/physics/pm4l5image1.jpg

❷

The journey thus far







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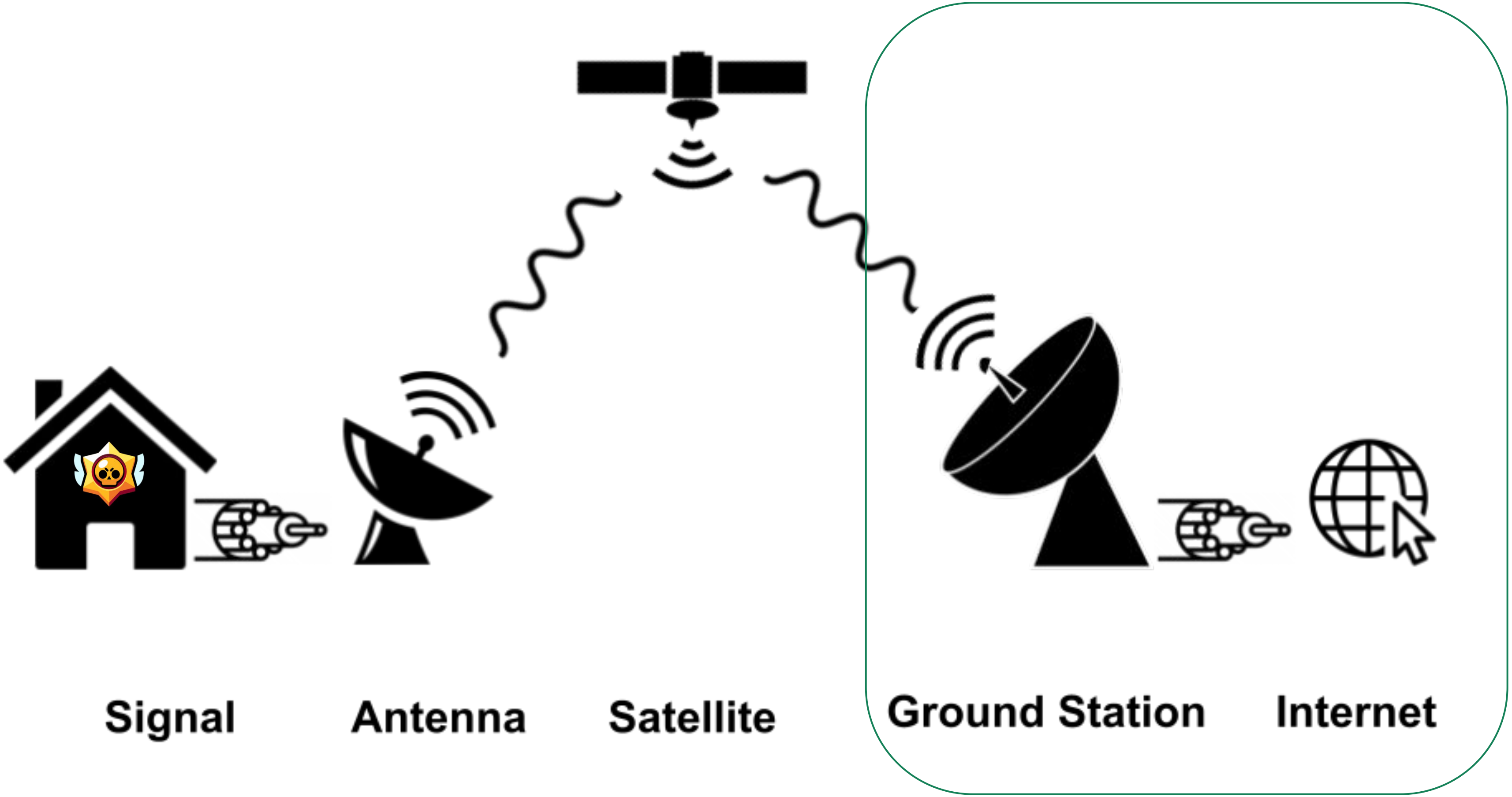

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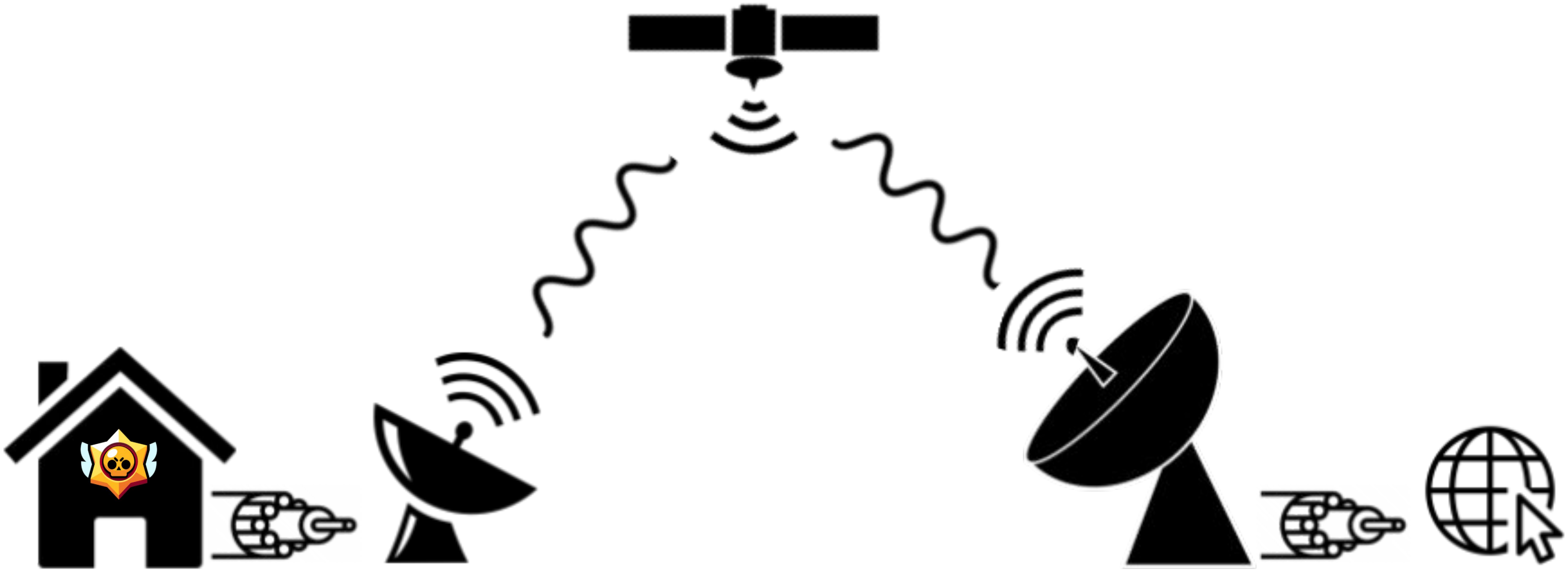
Starlink



Signal Antenna Satellite Ground Station Internet

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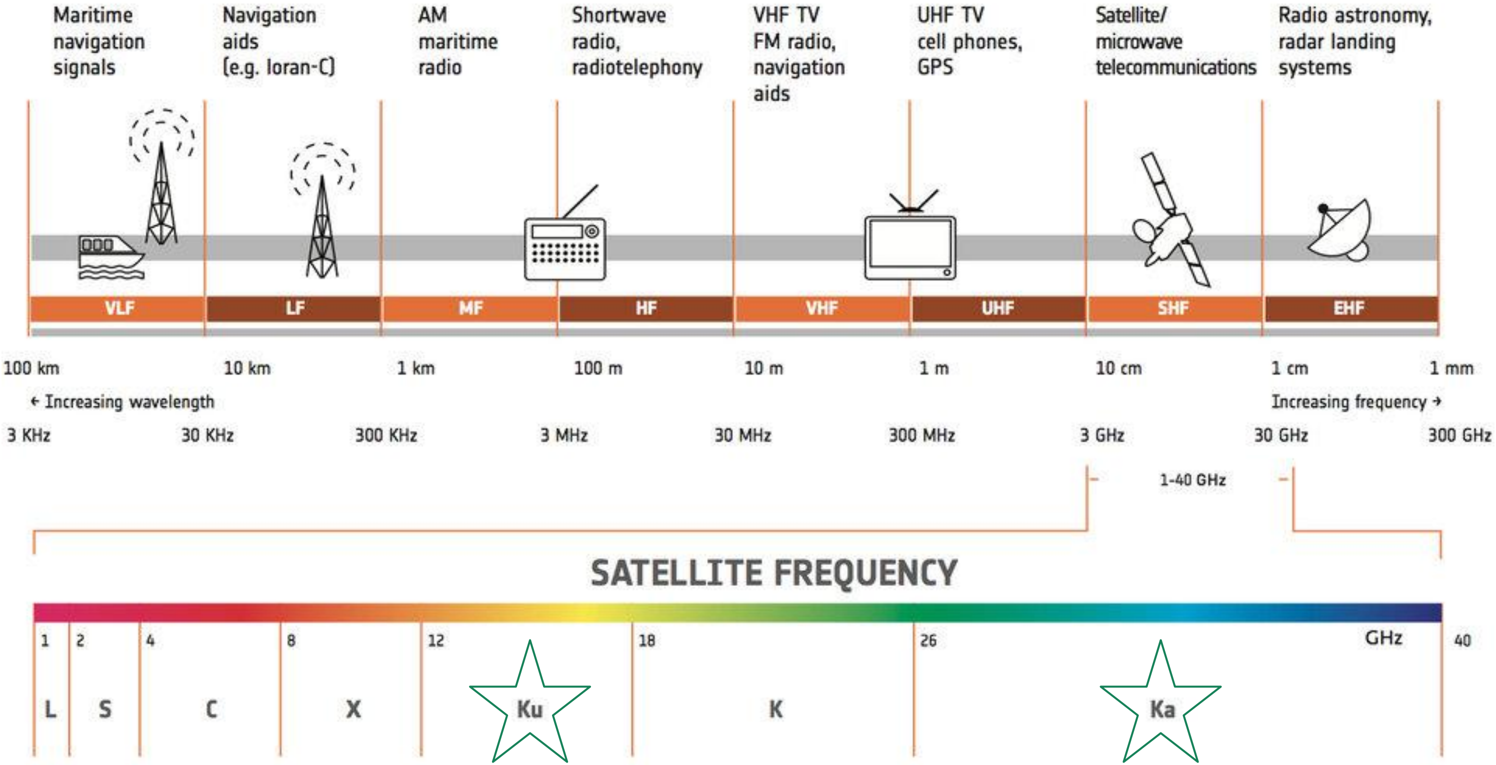
Starlink Signal



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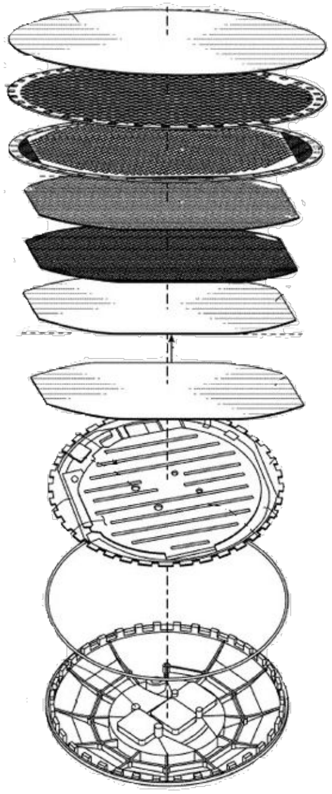
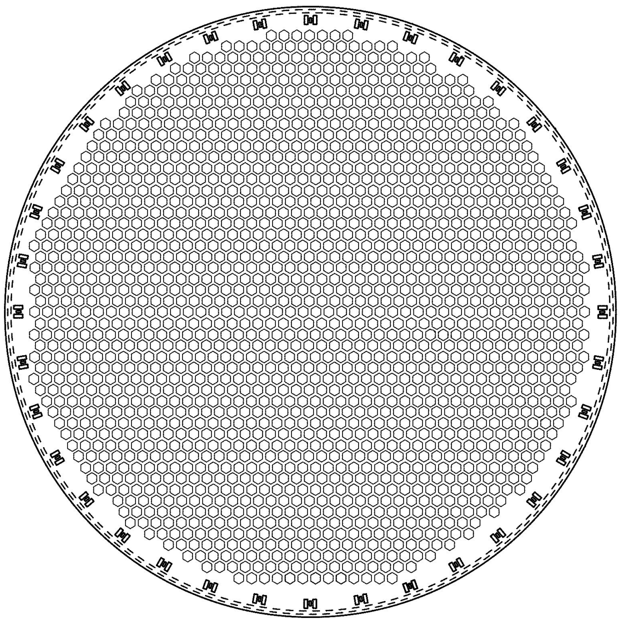
Dishy McFlatface (Antenna) Design

https://www.rvmobileinternet.com/wp-content/uploads/2021/11/first-gen-starlink-dish-dishy-300x300.png



https://uspto.report/patent/app/20200381816/US20200381816A1-20201203-D00004.png



https://uspto.report/patent/app/20200381816/US20200381816A1-20201203-D00010.png

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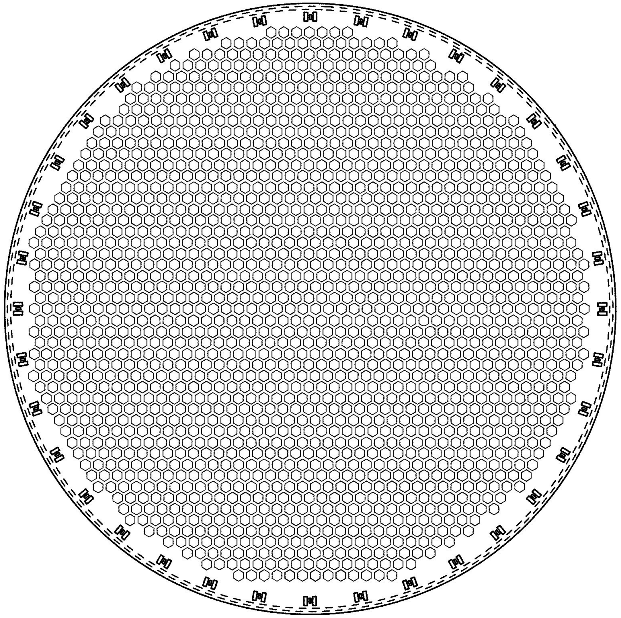
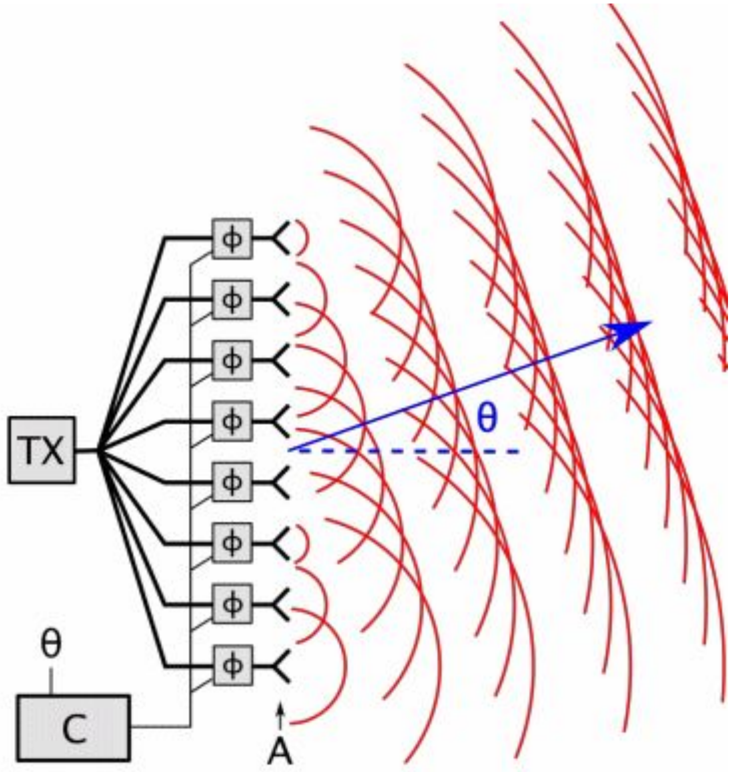
Array Interference





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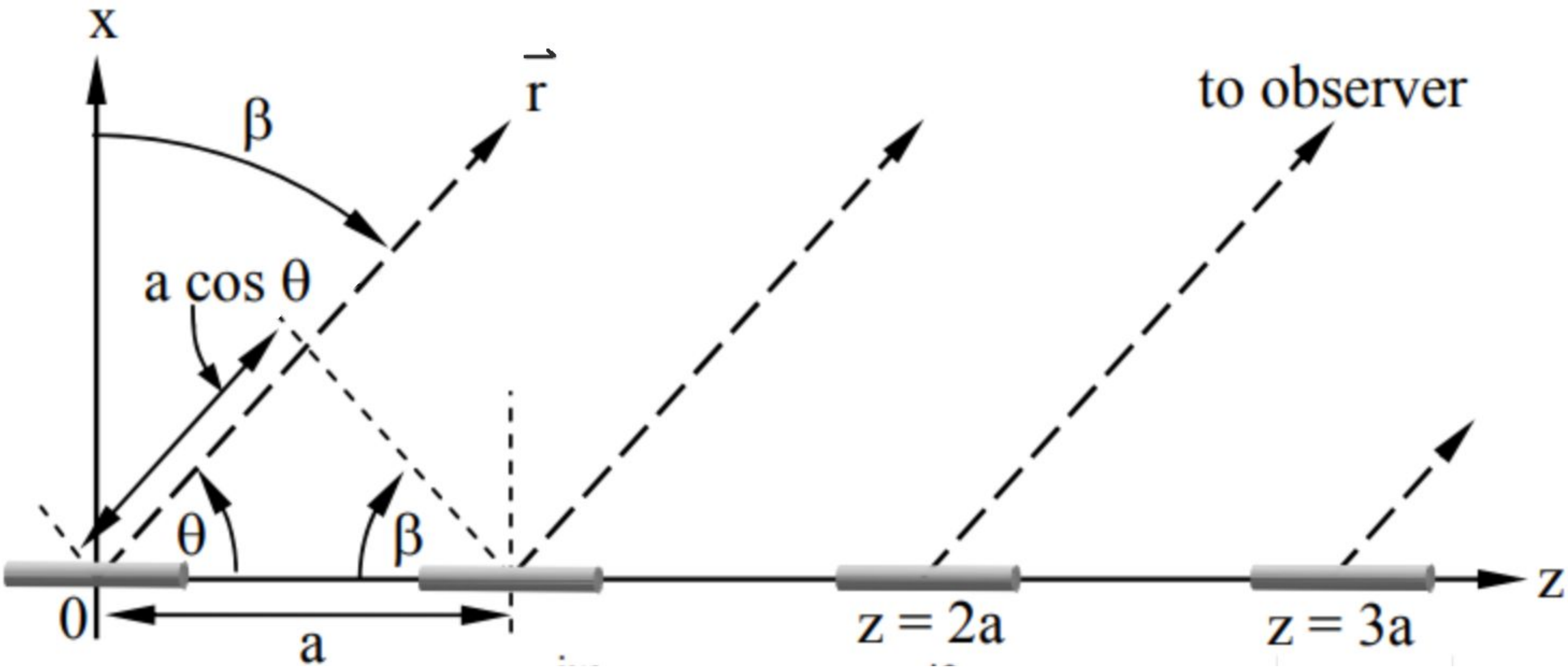
Beamforming

$$a\cos\theta = a\sin\beta = \frac{\lambda}{2\pi}\Delta\phi_a$$



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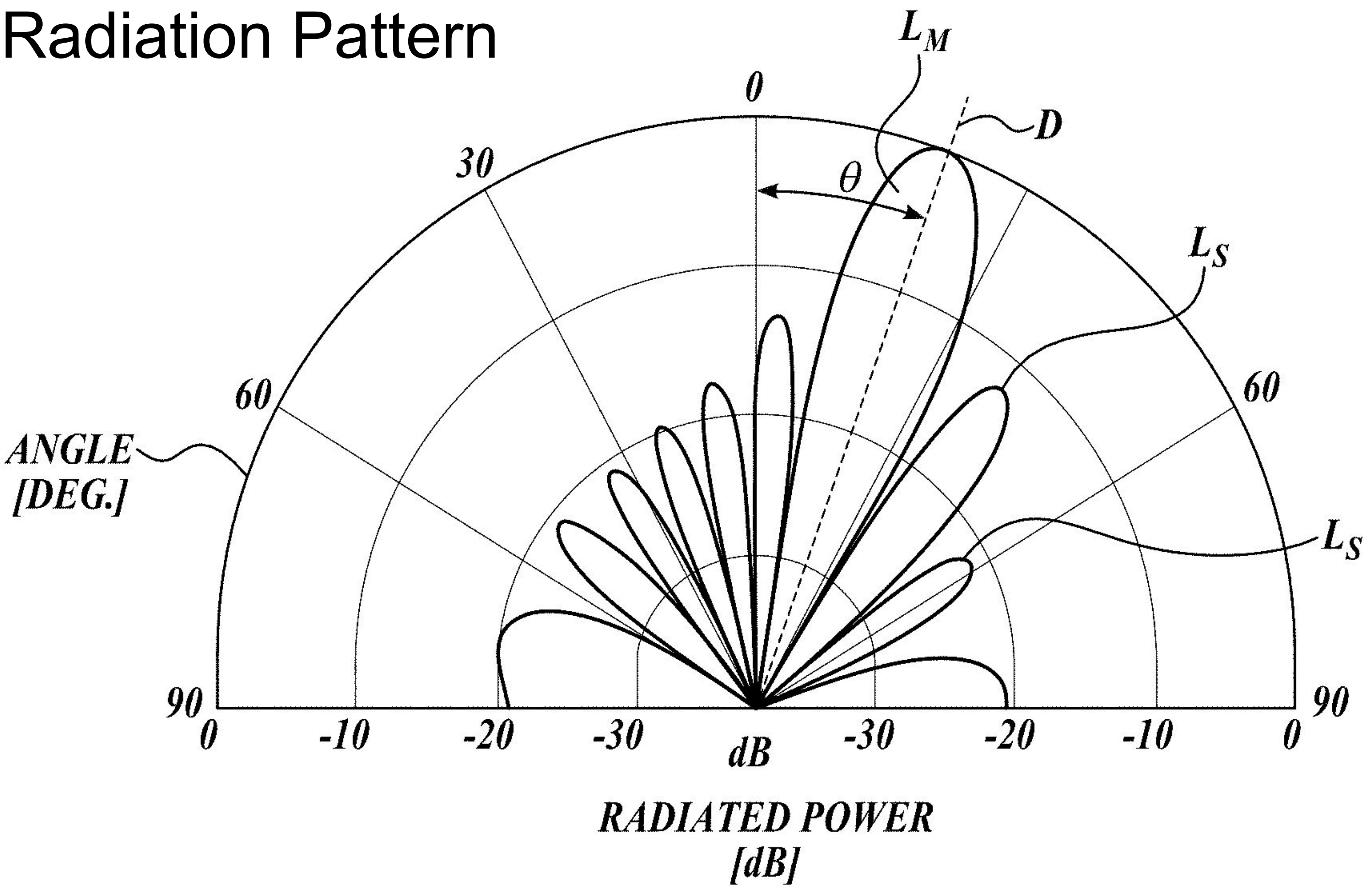
Dishy Radiation Pattern



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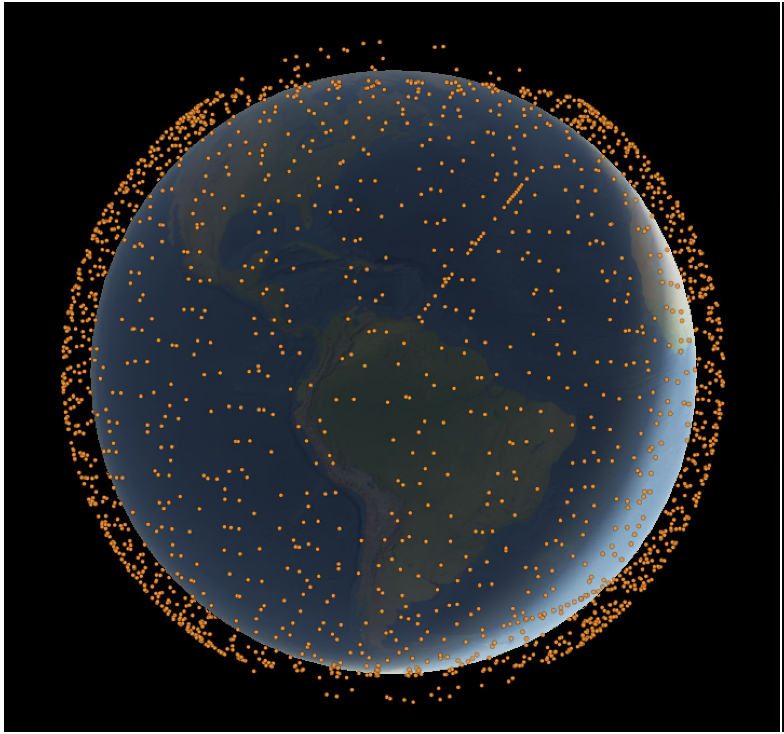
A new constellation?



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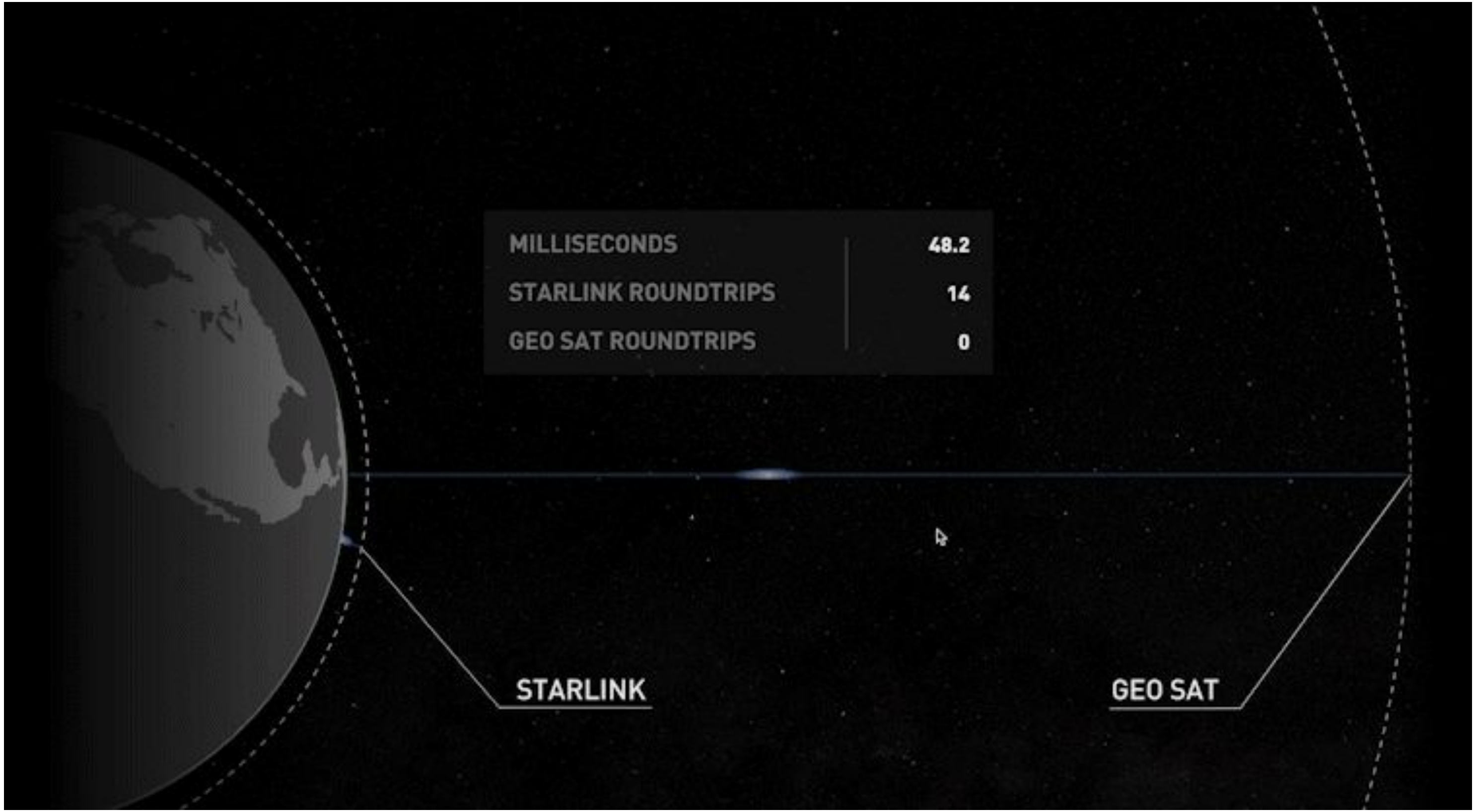
Why LEO and why now?

LATENCY!
and
FEASIBILITY!



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https://cdn2.vox-cdn.com/uploads/chorus_asset/file/6310881/landing_new_2.0.gif

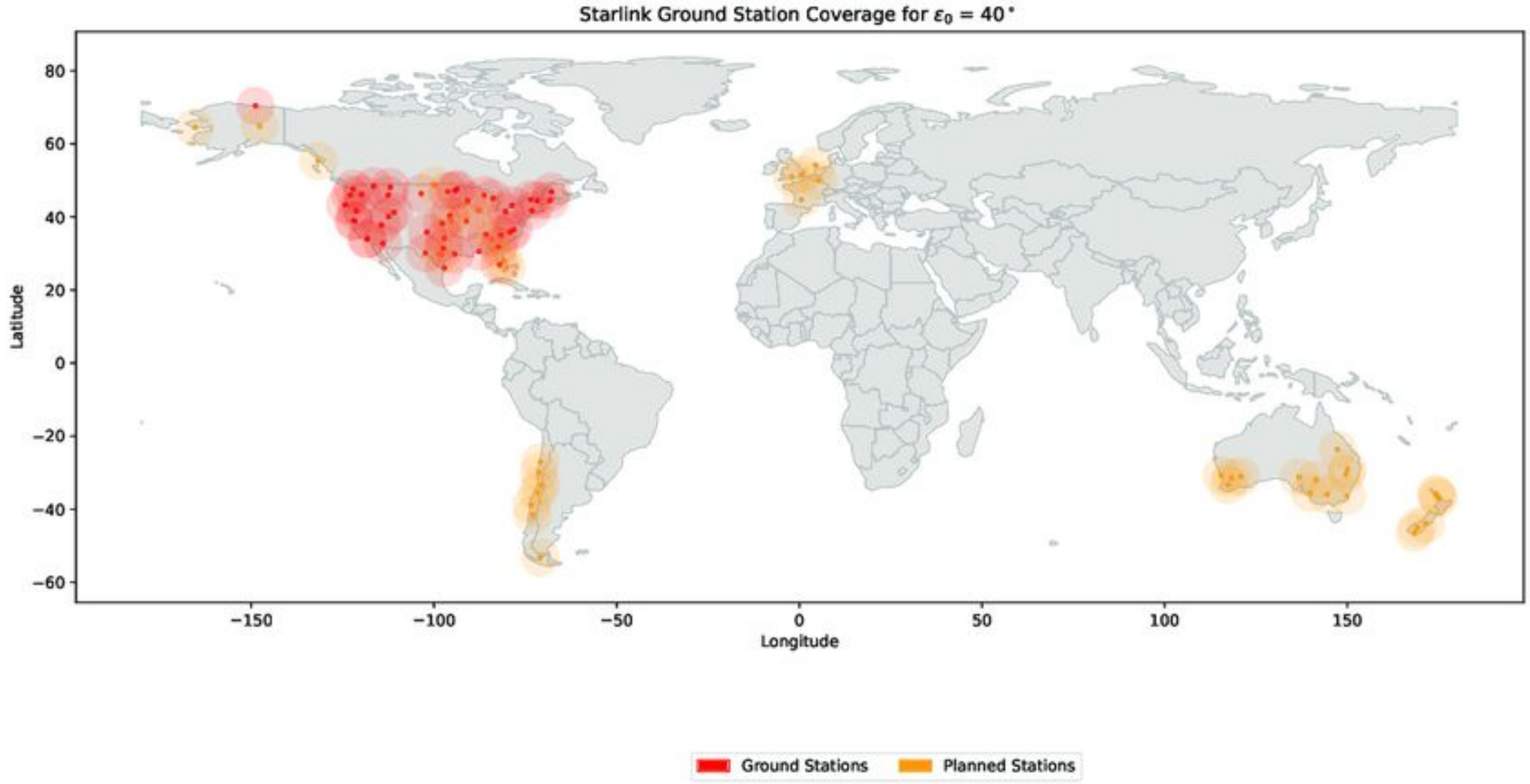
https://www.google.com/url?sa=i&url=https%3A%2F%2Fgfycat.com%2Fgifs%2Ftag%2Fstarlink&psig=AOvVaw0wy-rj99hMaYGDtNLobz2q&ust=1676050671104000&source=images&cd=vfe&ved=0CA4QjRxqFwoTCJjen7n9iP0CFQAAAAAdAAAAABBF

Deployment

https://upload.wikimedia.org/wikipedia/commons/thumb/9/91/Starlink_Mission_%2847926144123%29.jpg/600px-Starlink_Mission_%2847926144123%29.jpg

❸

Starlink Point of Presence (PoP)



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Starlink Concerns and Benefits

Concerns:

- Space debris
- Disrupt astronomical measurements

Benefits:

- Communication Disruptions
  - Natural Disasters
  - War
- Faster than cable Internet?