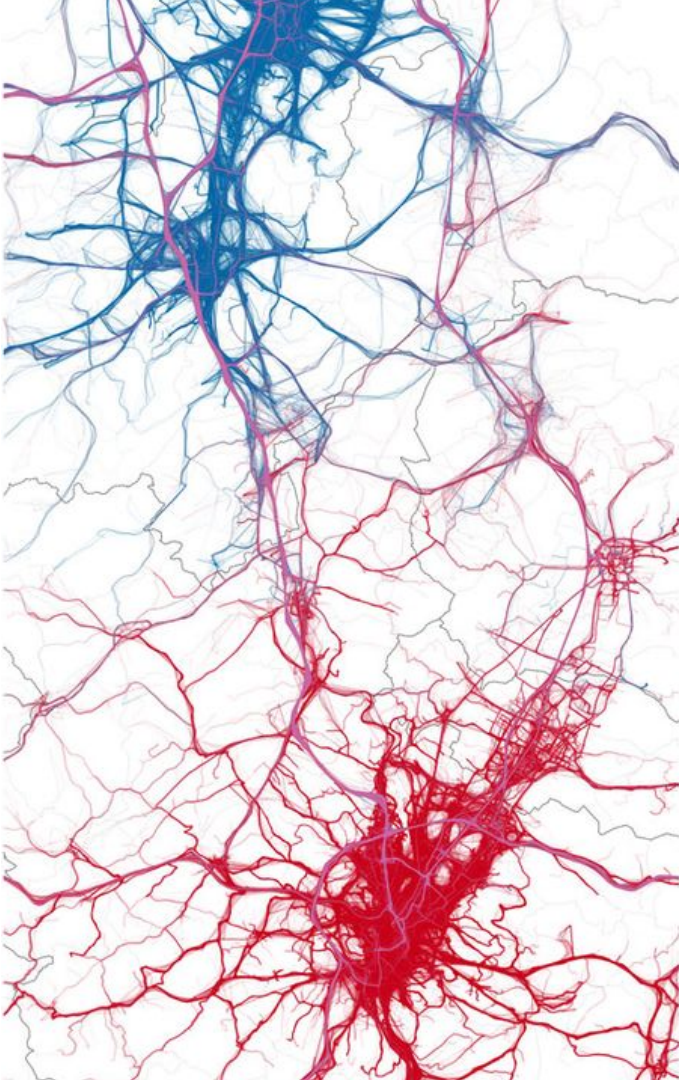




Consiglio Nazionale
delle Ricerche



Mobility Data



Tom Thumb scatters pebbles
along the path into the forest.

Illustration by **Gustave Doré**, “gravure sur
bois pour Les contes de Perrault”, 1867.



digital mobility data

Time-stamped records that capture human movement as
a by-product of digital activity.

Typically collected *passively*, they are used to reconstruct
trajectories and analyse mobility patterns.

Dimension	Digital mobility data	Traditional mobility data
Collection mode	Passive , automatically generated as a by-product of digital services	Active , based on deliberate self-reporting by individuals
Individual effort	Minimal or none	High (questionnaires, diaries, interviews)
Purpose of data generation	Operational (e.g., telecom, navigation, platforms)	Designed explicitly for mobility analysis
Semantic richness	Low (limited information on purpose and intent)	High (trip purpose, mode, socio-demographics)
Spatial-temporal coverage	Continuous, large-scale, long-term	Limited in time, space, and sample size
Scalability	Very high (millions of individuals)	Low to medium
Main limitations	Ambiguity, sampling bias, lack of context	Costly, recall errors, respondent burden

Exercise

Develop a method to collect data about the mobility of master students at the University of Pisa.

Rules:

- You cannot use smartphones or GPS devices
- You should cover as many students as possible
- The procedure should be as accurate as possible

No Internet nor AI.

10 minutes

census survey

Every 10 years

Systematic process of collecting information about an ***entire population***, conducted at the national level through standardized questionnaires administered by official statistical agencies.

sample survey

Process performed between census rounds to collect more detailed socio-demographic and mobility-related information from a (representative) ***subset of the population***.

Via Vignale 9	
Via Montaldo 45	

[NAME SURNAME]

D INFORMATION ABOUT THE ACCOMMODATION AT: [ADDRESS _\$]

D.0 During the year, do you live or sleep in the accommodation at [ADDRESS _\$]?

Answer Yes, even for shorter periods, such as a few months, a few weeks, or only on weekends.

1 Yes ➡ !"#\$%&'(\$)#*!+,-

2 No

If you answered 2 to question D.0

D.0.1 What type of accommodation is this?

(CAPI) Read the answers

1 It is an accommodation owned for sale/to let, rented, or vacant

2 It is an accommodation where other family members or relatives live

3 It is an accommodation used as a workplace (business office, medical practice, etc.)

4 It is an accommodation that has been sold

5 It is an accommodation I have rented

6 It is an accommodation that is uninhabitable or under construction

7 I have no information about this accommodation

8 Other type of accommodation ➡ *specify |

}

Go to the next section D if applicable or to section 1 if it has to be filled in or to 'Other information' section

If you answered 1 to question D.0

D.1 What type of accommodation is this?

(CAPI) Read the answers

1 It is the accommodation I live in

2 It is the accommodation I use during lessons and exam periods

3 It is the accommodation I use for work or professional training

4 It is the accommodation I return to when I stay with my family

Person 1 (continued)

30 a. LAST WEEK, did this person work for pay at a job (or business)?

☐ Yes ➡ SKIP to question 31

☐ No – Did not work (or retired)

31 b. LAST WEEK, did this person do ANY work for pay, even for as little as one hour?

☐ Yes

☐ No ➡ SKIP to question 36a

31 At what location did this person work LAST WEEK? If this person worked at more than one location, print where he or she worked most last week.

a. Address (Number and street name)

If the exact address is not known, give a description of the location such as the building name or the nearest street or intersection.

b. Name of city, town, or post office

c. Is the work location inside the limits of that city or town?

☐ Yes

☐ No, outside the city/town limits

d. Name of county

e. Name of U.S. state or foreign country

f. ZIP Code

32 How did this person usually get to work LAST WEEK? Mark (X) ONE box for the method of transportation used for most of the distance.

☐ Car, truck, or van	☐ Taxi or ride-hailing services
☐ Bus	☐ Motorcycle
☐ Subway or elevated rail	☐ Bicycle
☐ Long-distance train or commuter rail	☐ Walked
☐ Light rail, streetcar, or trolley	☐ Worked from home ➡ SKIP to question 40a
☐ Ferryboat	☐ Other method

33 Answer question 33 if you marked "Car, truck, or van" in question 32. Otherwise, SKIP to question 34.

33 How many people, including this person, usually rode to work in the car, truck, or van LAST WEEK?

Person(s)

34 LAST WEEK, what time did this person's trip to work usually begin?

Hour : Minute ☐ a.m. ☐ p.m.

35 How many minutes did it usually take this person to get from home to work LAST WEEK?

Minutes

36 Answer questions 36 – 39 if this person did NOT work last week. Otherwise, SKIP to question 40a.

36 a. LAST WEEK, was this person on layoff from a job?

☐ Yes ➡ SKIP to question 36c

☐ No

b. LAST WEEK, was this person TEMPORARILY absent from a job or business?

☐ Yes, on vacation, temporary illness, maternity leave, other family/personal reasons, bad weather, etc. ➡ SKIP to question 39

☐ No ➡ SKIP to question 37

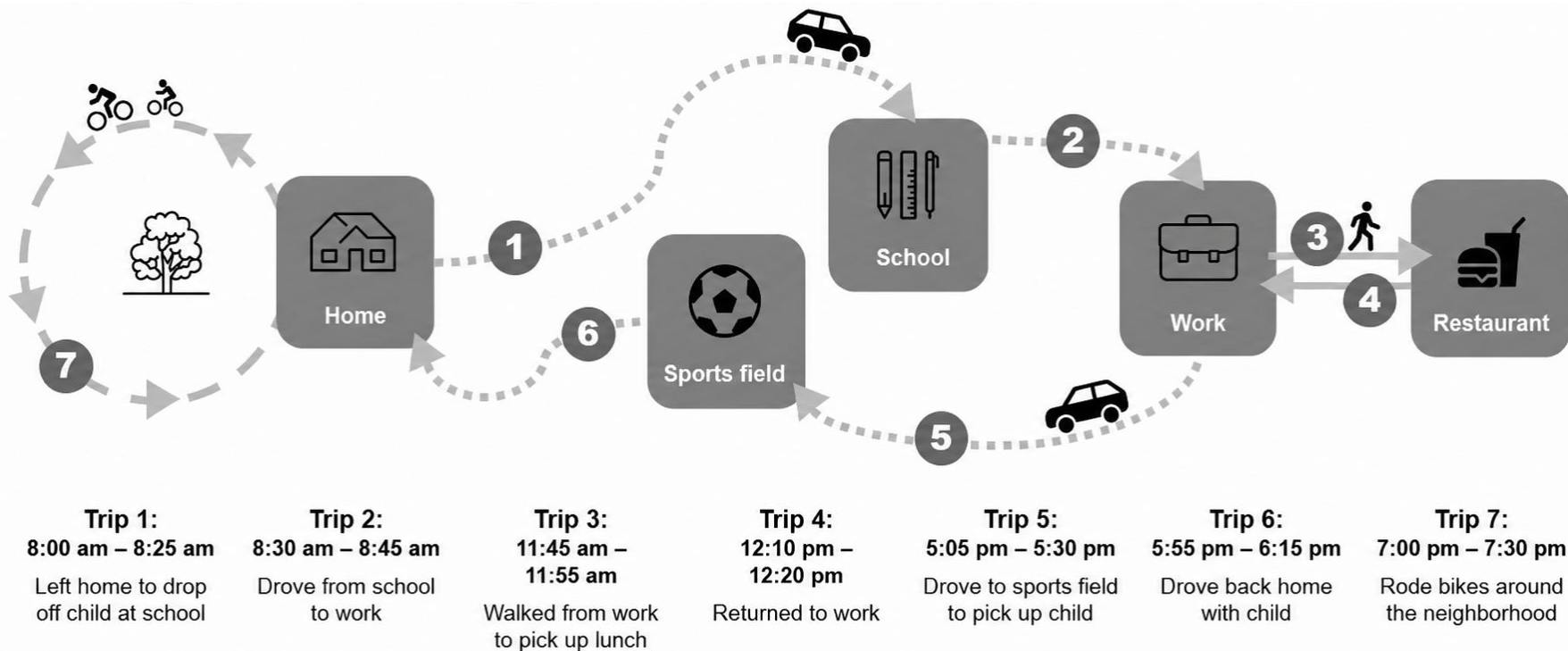
c. Has this person been informed that he or she will be recalled to work within the next 6 months OR been given a date to return to work?

☐ Yes ➡ SKIP to question 38

☐ No

travel survey

Structured data collection studies, typically implemented through ***diary-based instruments***, in which a sampled group of individuals reports ***all trips*** made over one or several days, including origins and destinations, departure and arrival times, transport modes, and trip purposes.



One-day travel survey diary, U.S. Department of Transportation travel survey

Quiz 1

Is this a census survey, a sample survey or a travel survey?

Quiz 1

Is this a census survey, a sample survey or a travel survey?

- Every household in a town is asked to record all trips made by its members yesterday.

census survey

travel survey

Quiz 1

Is this a census survey, a sample survey or a travel survey?

- A randomly selected group of 500 residents is asked how they usually travel to work.

sample survey

Quiz 1

Is this a census survey, a sample survey or a travel survey?

- Every student at a university is asked to report information about place/date of birth, residence address, health status, ..

census survey

Quiz 1

Is this a census survey, a sample survey or a travel survey?

- Researchers ask 30 volunteers at a bus stop where they are going and which mode of transport they used to get there.

sample survey

Quiz 2

Each statement contains a mistake or is incomplete. Rewrite it correctly.

- “A travel survey is always a sample survey.”

In principle, a *travel survey* can be a sample survey or a census survey. Typically, it is a sample survey.

Quiz 2

Each statement contains a mistake or is incomplete. Rewrite it correctly.

- “A survey of every resident in a city about their commuting is a sample survey because it asks about travel.”

If every resident in the defined population is surveyed, it is a census survey.

Quiz 2

Each statement contains a mistake or is incomplete. Rewrite it correctly.

- “A survey of 200 randomly selected households about their income is a travel survey.”

This is a sample survey because it covers only some households. It is not necessarily a travel survey because it asks about income, not journeys or travel behavior.

Quiz 2

Each statement contains a mistake or is incomplete. Rewrite it correctly.

- “A survey of all employees in a company about their journeys to work is both a census survey and a travel survey.”

It includes every employee, so it is a census survey; it asks about journeys to work, so it is also a travel survey.

Dimension	Census	Sample survey	Travel survey
Primary purpose	Population enumeration and structural statistics	Population estimation with enhanced detail	Detailed analysis of individual travel behaviour
Population coverage	Entire population	Representative sample of the population	Sampled population (hundreds to thousands)
Temporal scope	Single reference date	Typical week or year	One or several consecutive days
Mobility information collected	Residence, basic migration indicators	Residence, workplace or school, commuting mode, average travel time	All trips made, with origins, destinations, times, purposes, and modes
Semantic richness	Low	Low to moderate	High
Spatial resolution	Administrative units	Administrative units	Trip-level, sometimes address-based
Main strengths	Full coverage, comparability, long-term trends	Representativeness with richer attributes	Behavioural detail, mode choice, activity patterns
Main limitations	Infrequent, static view	Sampling error, limited temporal detail	High cost, respondent burden, limited scale

DID YOU KNOW THAT?

A census has been
used to date the
birth of Jesus



Byzantine mosaic (c. 1315 CE, Chora Church, Istanbul) depicts governor Quirinius (seated, left) overseeing the census registration of Mary and Joseph (haloed, right).

Luke 2:1-20

“ In those days a decree went out from Caesar Augustus that ***all the world should be registered***. This was the first registration and was taken while Quirinius was governor of Syria. All went to their own towns to be registered. Joseph also went from the town of Nazareth in Galilee to Judea, to the city of David called Bethlehem [...]. He went to be registered with Mary, to whom he was engaged and who was expecting a child. ”

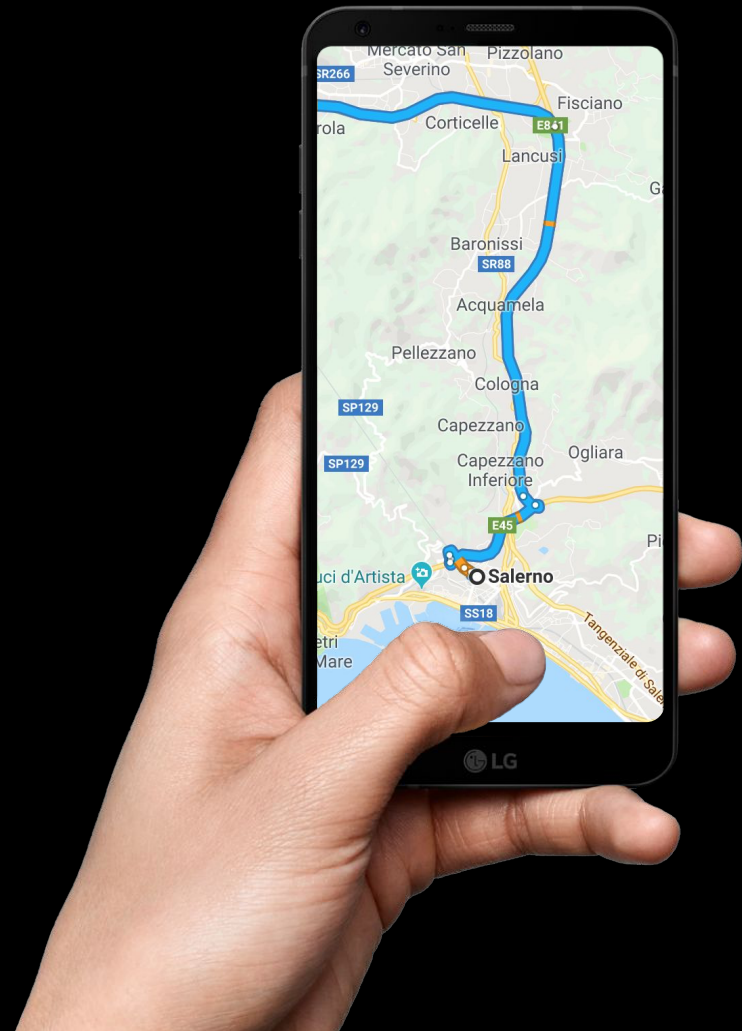
A longstanding controversy

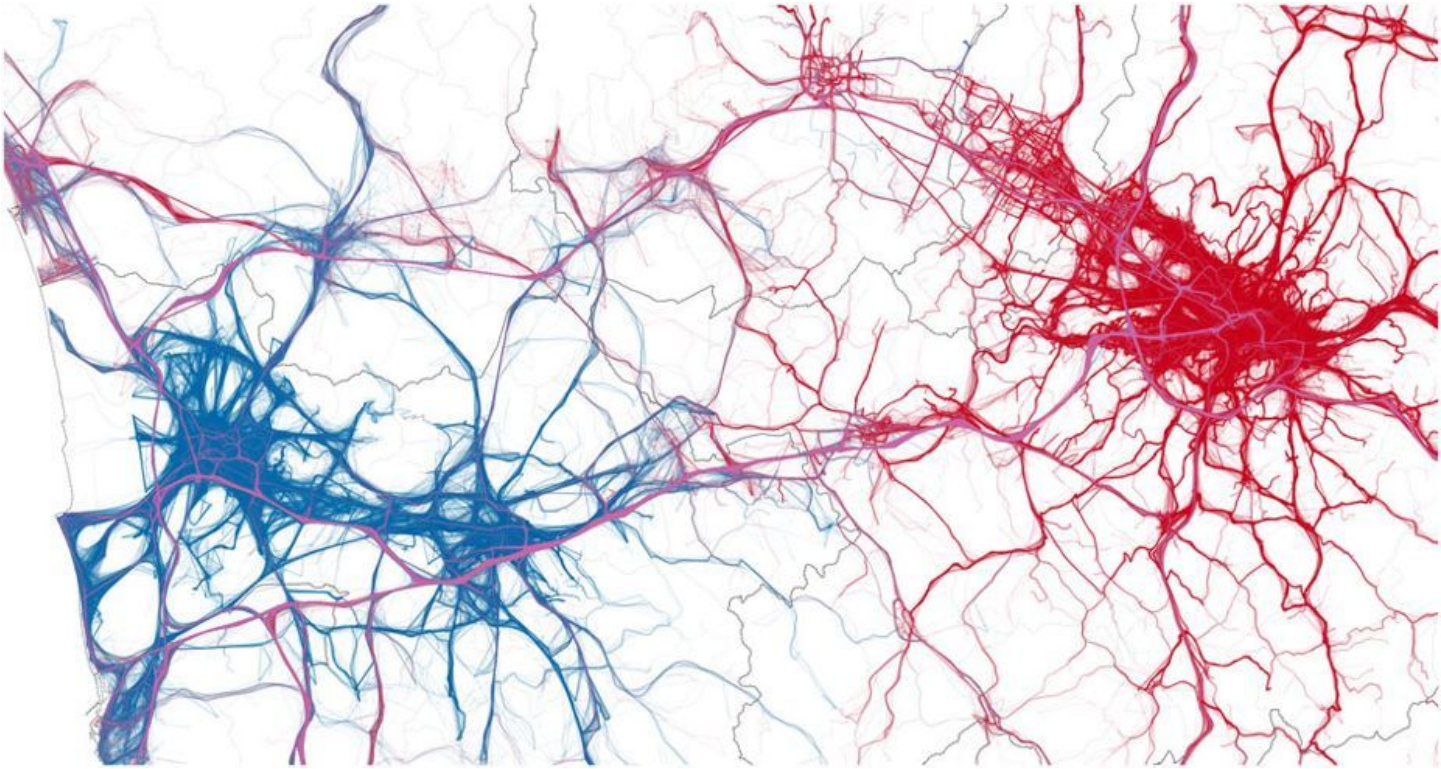
Roman records indicate that Quirinius conducted a census in Judea around **6–7 AD**.

This timing conflicts with other historical sources that place the birth of Jesus earlier, during the reign of Herod the Great, who died in **4 BCE**.

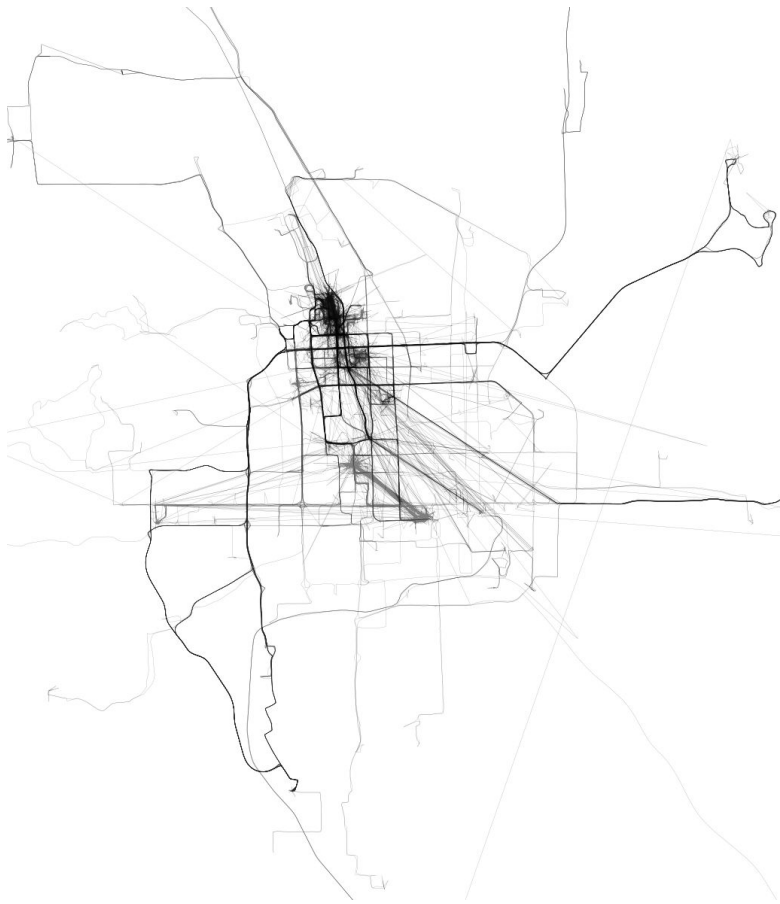
Reconciling these accounts has been the subject of centuries of scholarly debate (still open), involving interpretations of Roman administrative practices and translation nuances.

GPS data





GPS trajectories representing the movements of around 50k cars between the area of Pisa (left, in blue) and Florence (right, in red) during May 2011.



GPS trajectories in Beijing Microsoft
GeoLife dataset

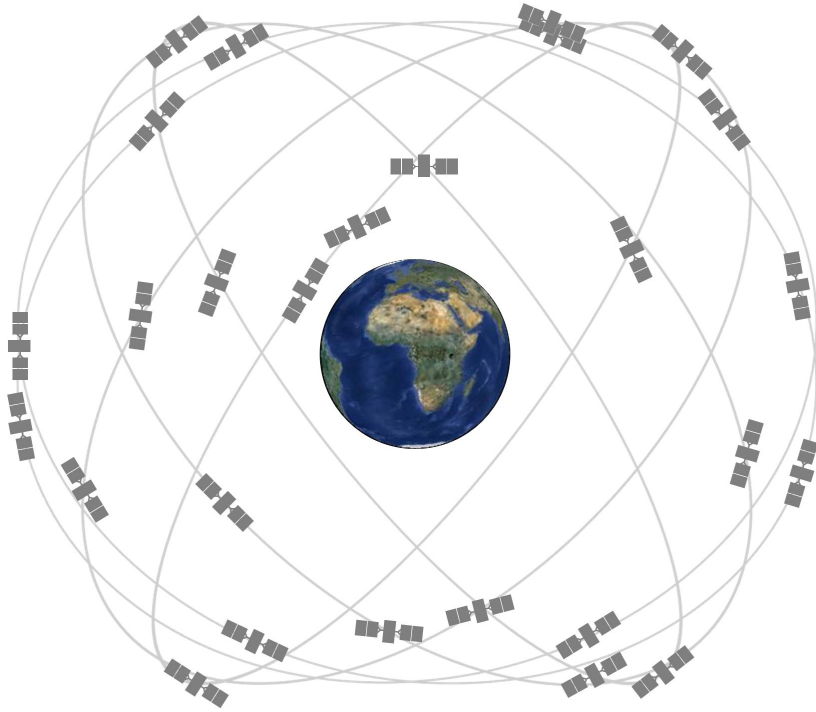


Taxi trajectories in San Francisco
CROWDAD EPFL/mobility dataset.

Global Positioning System (GPS)

- Most known GNSS (global navigation satellite system)
- Complete name: NAVTEC GPS
- US-owned utility providing users with positioning, navigation, and timing (PNT) services
- A system made of three main components:
 - a. Space segment
 - b. Control segment
 - c. User segment

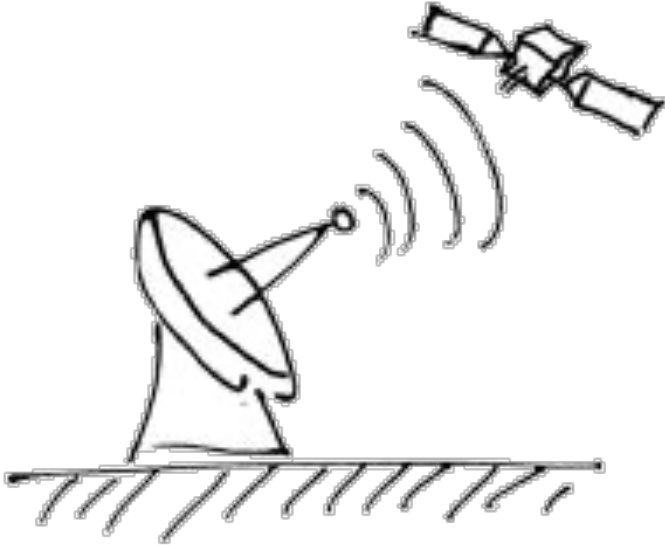
1) Space segment



24+ satellites, each

- orbiting at 20,000 km
- circling Earth twice a day in six equally-spaced orbits
- broadcasting a radio signal
- each orbit contains four satellites
- users view at least four satellites from any point

2) Control segment



Ground facilities that:

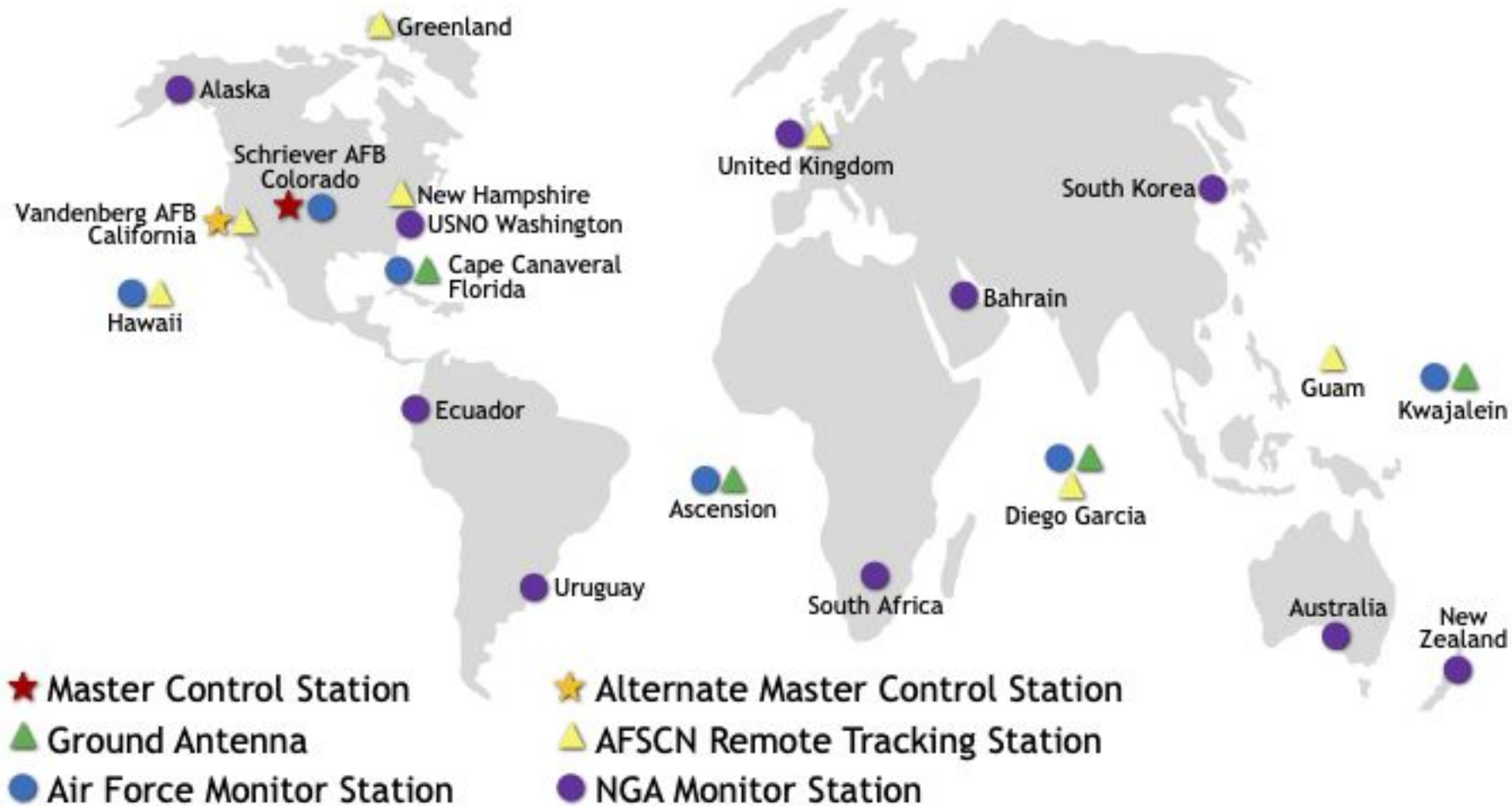
1. track the GPS satellites
2. monitor their transmissions
3. perform analyses
4. send commands and data to the constellation

2) Control segment

The current Operational Control Segment (OCS) includes:

1. a master control station
2. an alternate master control station
3. 11 command and control antennas
4. 16 monitoring sites

The GPS constellation delivers high performance thanks to the dedicated efforts of its operators (nicknamed Team Blackjack)



3) User segment

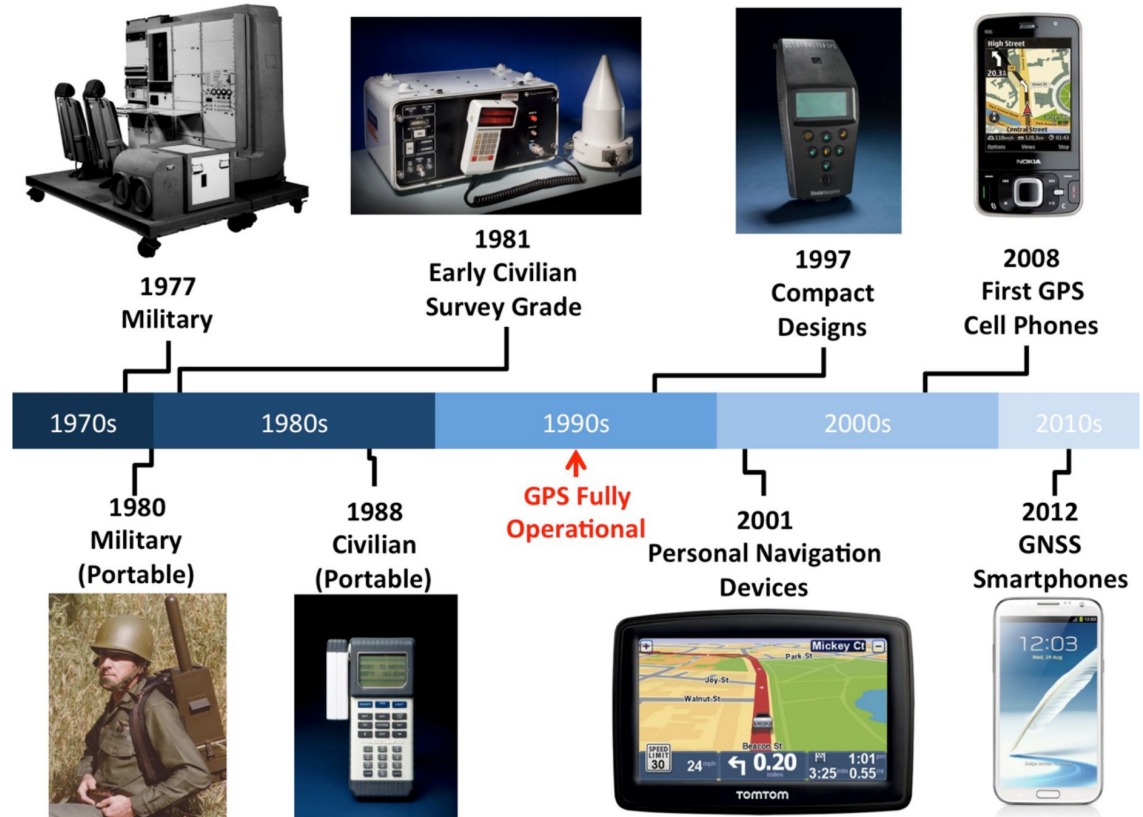


GPS is everywhere:

- cell phones
- wristwatches
- bulldozers
- shipping containers
- ATM's
- sports bras
- ...

3) User segment

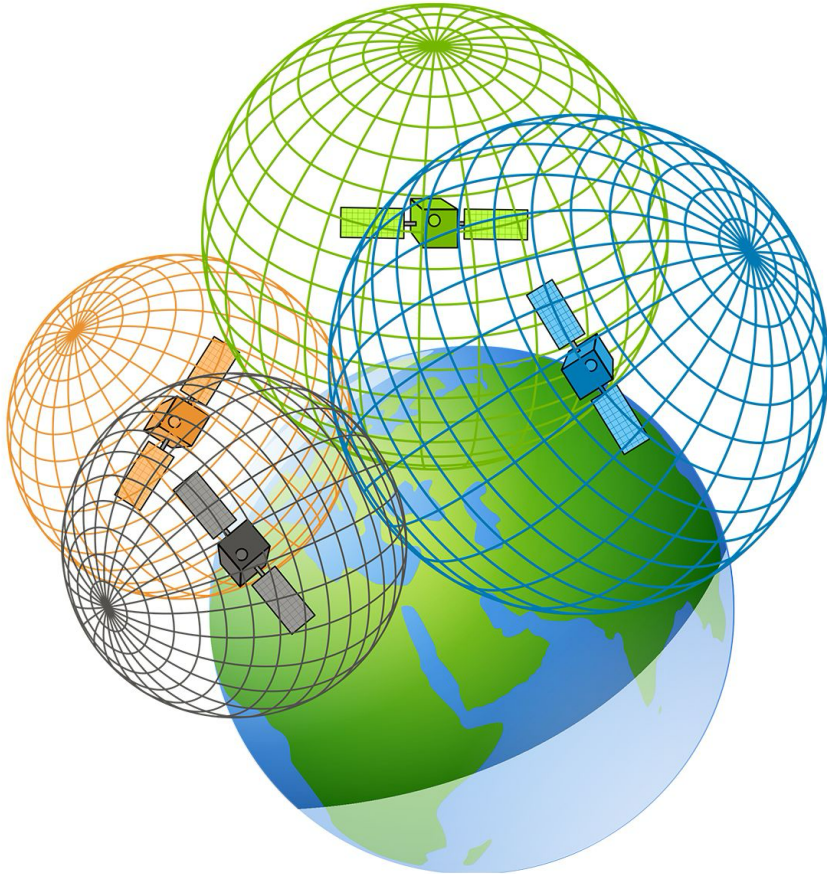
GPS has not always been that small...



How does GPS work?

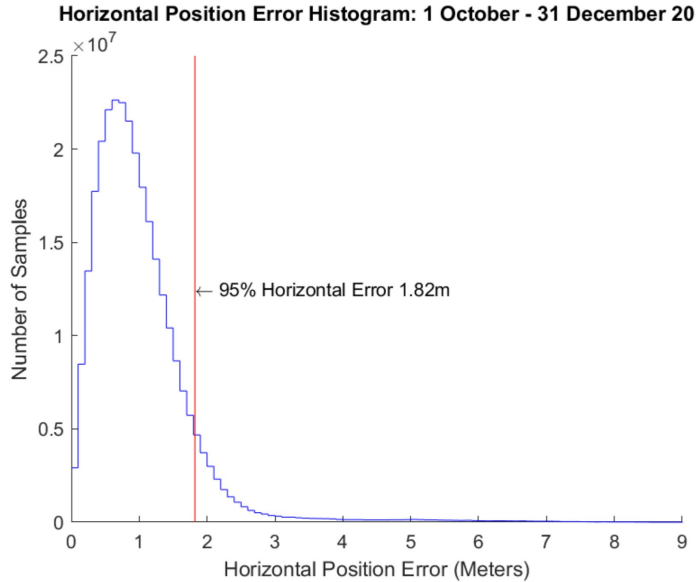
1. GPS satellites broadcast radio signals at the speed of light $\{c\}$ providing their locations, status, and precise time $\{t_1\}$ from on-board atomic clocks
2. A GPS device receives the signals, noting exact time of arrival $\{t_2\}$ to calculate its distance from the satellite
3. Once the device knows distance from at least four satellites, it can determine its location on Earth in three dimensions

Trilateration

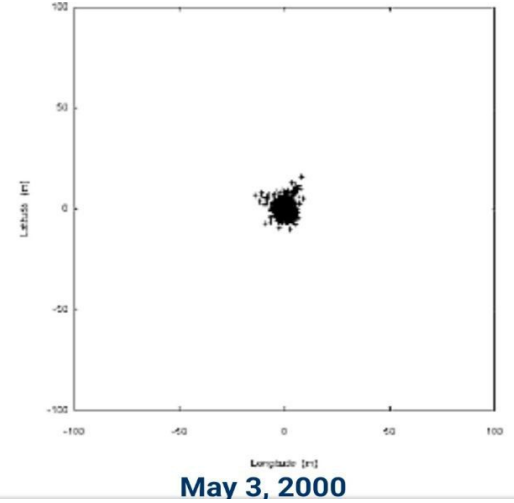
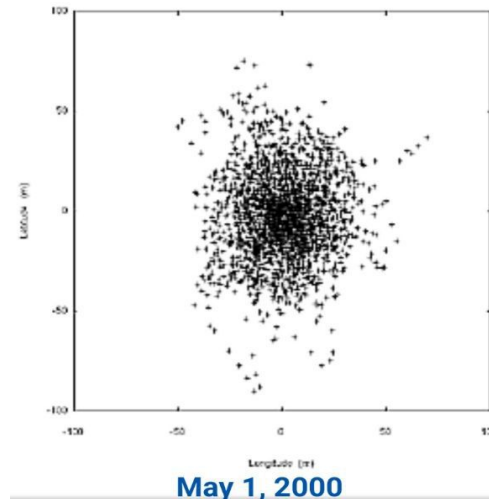


- Each satellite broadcasts a signal that eventually hits the GPS receiver
- The distance between the device and the satellite forms a sphere
- Where all spheres intersect determines the device's position
- At least three satellites needed to accurately position a device

Precision of GPS



https://www.nstb.tc.faa.gov/reports/2020_Q4_SPS_PAN_v2.0.pdf#page=38



GPS errors before and after "Selective Availability" was abolished by President Clinton, in 2000.

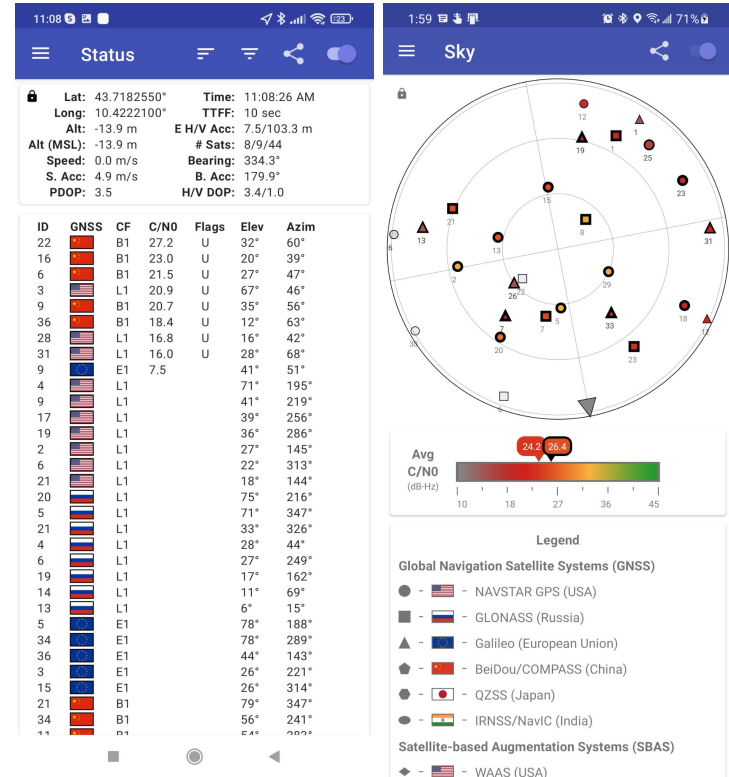
<https://www.gps.gov/systems/gps/modernization/sa/data/>

GPS is not the only GNSS

		Present (2017)			Future		
Core Const.	Owner	Total Number of Operational Satellites	Orbit Type	Configuration	Total Number of Operational Satellites	Orbit Type	Configuration
GPS	USA	31	MEO	6 Planes	24	MEO	6 Planes
GLONASS	Russia	24	MEO	3 Planes	24	MEO	3 Planes
Galileo	Europe	15	MEO	3 Planes	24	MEO	3 Planes
BeiDou	China	19	MEO	6 Satellites in 2 Planes	35	MEO	27 Satellites in 3 Planes
			IGSO	8 Satellites		IGSO	3 Satellites
			GEO	5 Satellites		GEO	5 Satellites

Source: <https://searchworks.stanford.edu/view/12064597>

<https://gnssplanning.com/#/settings>



GPSTest Android app

<https://orbitalradar.com/>

GPS traces format

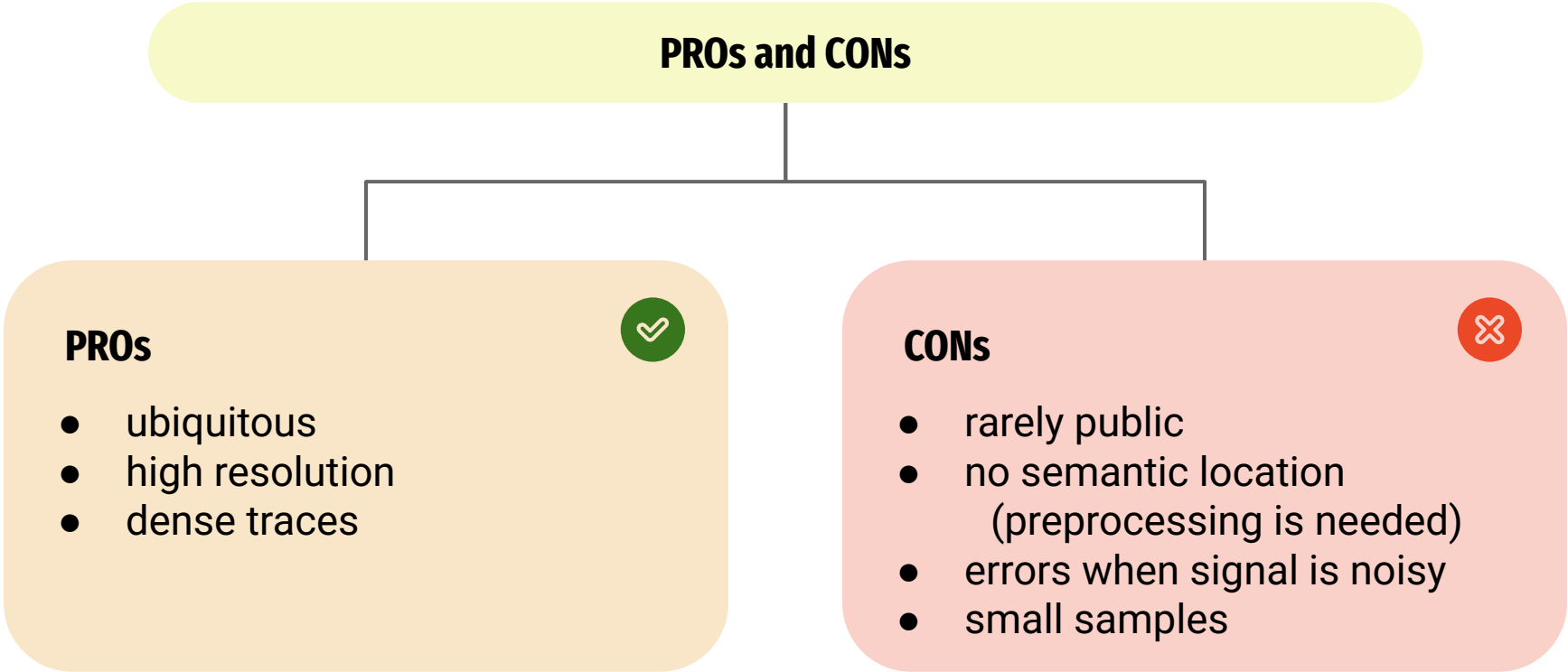
(u, lat, lng, alt, t)

device  time

position

- Sampling rate from few secs to 1-2 minutes
- Spatial precision 10 m

PROs and CONs



```
graph TD; A[PROs and CONs] --> B[PROs]; A --> C[CONs];
```

PROs



- ubiquitous
- high resolution
- dense traces

CONs



- rarely public
- no semantic location
(preprocessing is needed)
- errors when signal is noisy
- small samples

Bias	Main sources	What it means for analysis
Spatial resolution	Atmospheric effects, buildings, indoor settings, vegetation, and device quality.	Positions may be inaccurate or missing. GPS jitter can create false movement and inflate distance.
Temporal resolution	Device settings and battery-saving strategies cause irregular location updates or tracking gaps.	Short trips, brief stops, and rapid changes in travel mode may be missed; comparisons across devices or groups can be unreliable.
Semantic resolution	GPS records locations, but not activities, transport modes, trip purposes, or whether nearby points form one visit or journey.	Visits, stops, trips, and activities must be inferred using modelling choices and contextual data such as POIs, land use, and transport networks.
Representativeness	Coverage depends on who owns a GPS-enabled device, enables tracking, and how they use it. Some devices and activities are recorded more often than others.	Some groups and modes may be underrepresented; for example, vehicle-based data can overrepresent driving. Coverage may also be uneven across times and seasons.

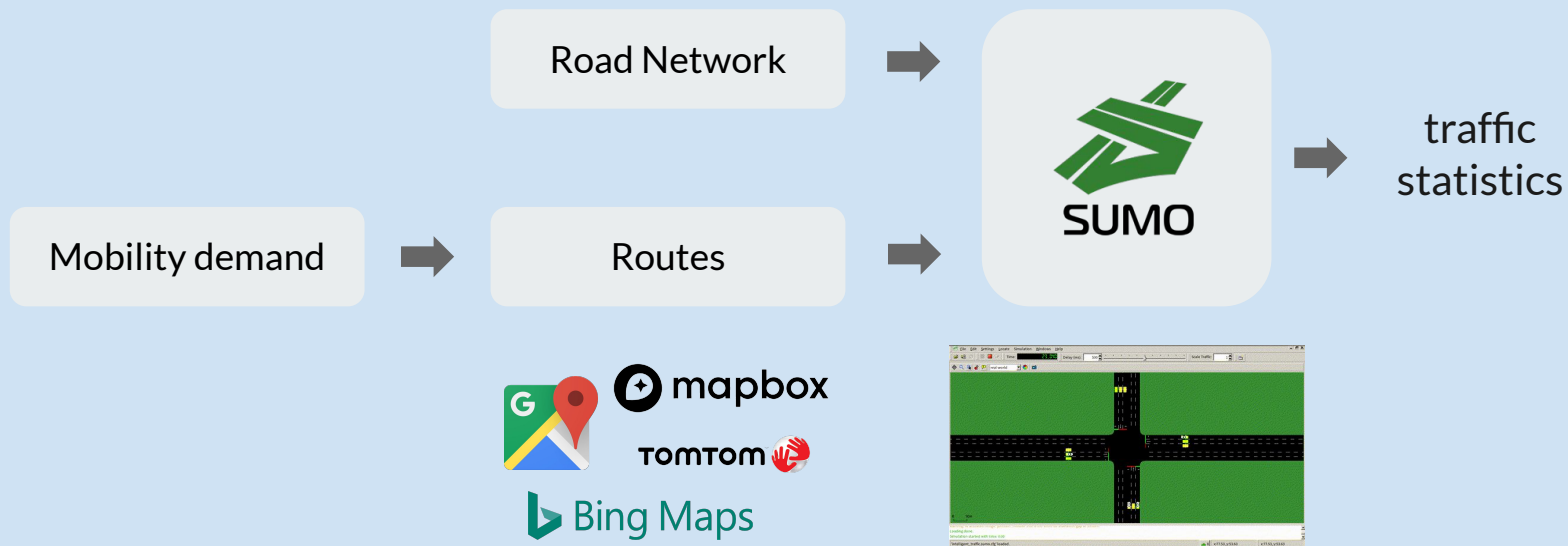
References

- [webpage] [GPS Overview](#), gps.gov, 2021
- [webpage] [Trilateration](#), GIS Geography, 2022
- [paper] [A survey of deep learning for human mobility](#), Pappalardo et al., ACM Computing Surveys, 2021
 - Appendix C.2
- [Book] **Pinpoint**, Greg Milner, W. W. Norton & Company; 1st edition, 2017
- [Episode] [Watch history](#), Netflix, season 2 - GPS



DID YOU KNOW THAT?

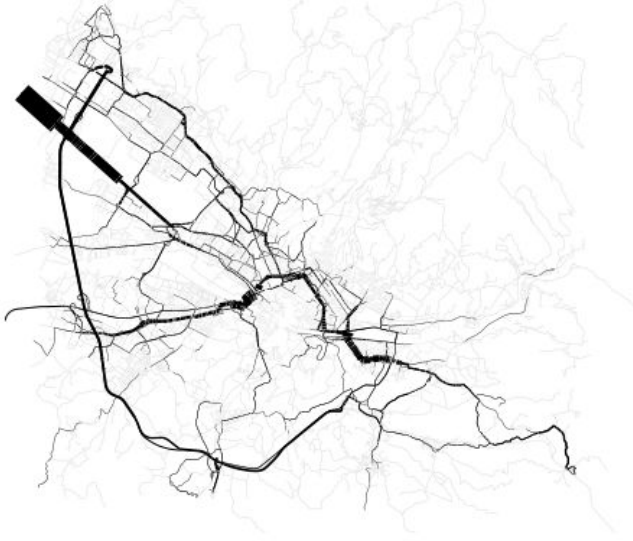
GPS navigation has
a substantial
cognitive and urban
impact



Cornacchia et al., How routing strategies impact urban emissions. 2022, ACM SIGSPATIAL

TomTom Fastest adoption: 0 %

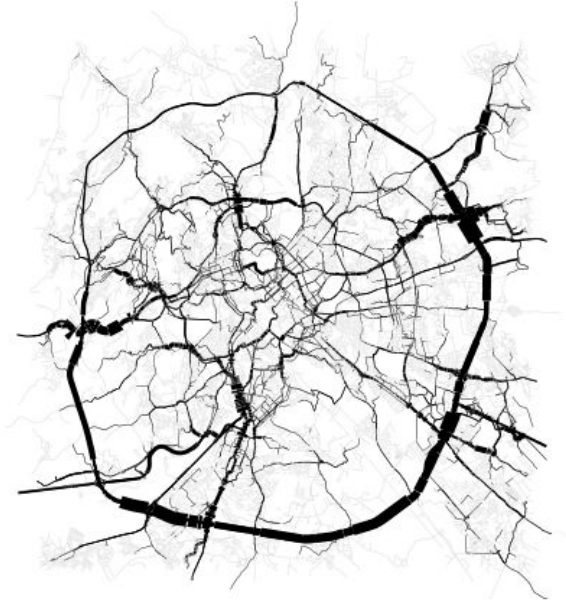
Florence



Milan

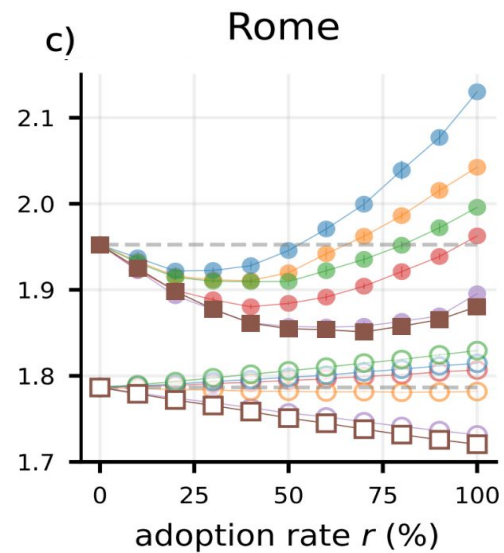
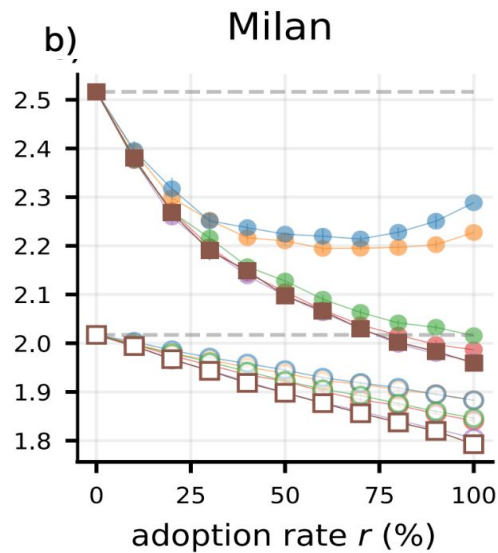
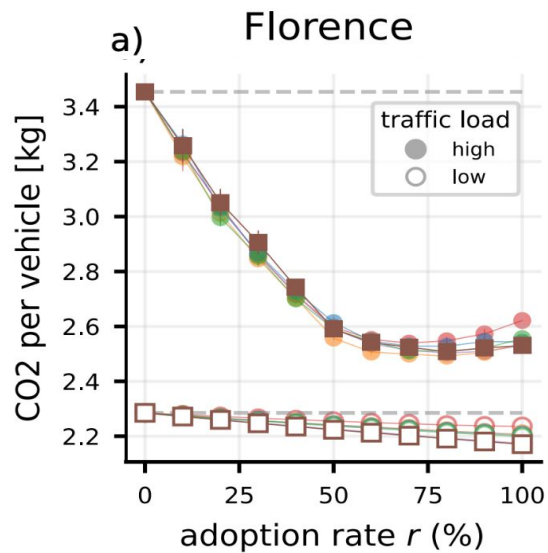


Rome

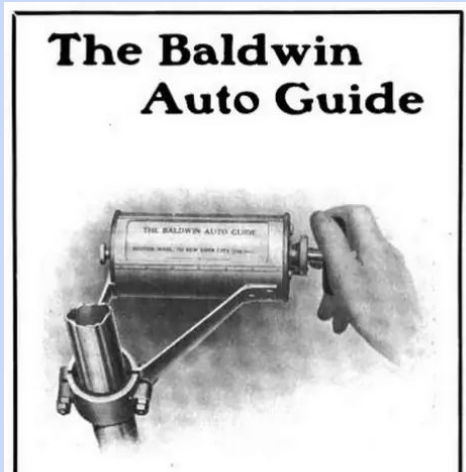


Cornacchia et al., The traffic concentration effects of urban navigation services, Nature Communications, 2026

--- no impact ● TTF ● TTS ■ ecoTT ● MB ● Bi ● GM



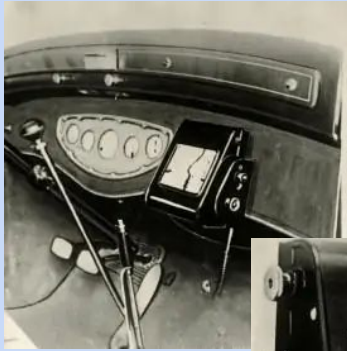
Who needs GPS? Early automobile navigation systems



+70 years before commercial uses of GPS for navigation, inventors developed automobile navigation devices:

- 1909: The Baldwin Auto Guide describes a scrolled map that attached to the steering wheel

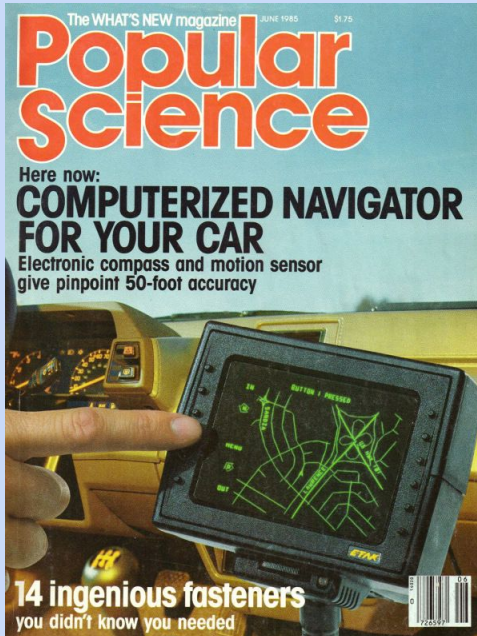
Who needs GPS? Early automobile navigation systems



+70 years before commercial uses of GPS for navigation, inventors developed automobile navigation devices:

- 1930: Iter Avto (Touring Club Italiano) added a level of automation by tethering the map scroll to the car's speedometer.

Who needs GPS? Early automobile navigation systems



+70 years before commercial uses of GPS for navigation, inventors developed automobile navigation devices:

- 1985: Story of Etak's Amazing 1985 Car Navigation System

References

- [Video] [How did Polynesian wayfinders navigate the Pacific Ocean?](#)
YouTube, TED-Ed channel
- [Article] [Before there was the GPS](#), GIS Lounge, 2013
- [Article] [Who Needs GPS? The Forgotten Story of Etak's Amazing 1985 Car Navigation System](#), FastCompany, 2015

Quiz

For each question, identify the GPS segment: space segment, control segment, or user segment.

- A ground station monitors a GPS satellite's orbit and checks whether its onboard clock is accurate. Which segment is involved?

control segment

Quiz

For each question, identify the GPS segment: space segment, control segment, or user segment.

- A ship's navigation device receives signals from several satellites and calculates its position. Which segment does the device belong to?

user segment

Quiz

For each question, identify the GPS segment: space segment, control segment, or user segment.

- A GPS satellite broadcasts its signal to receivers on Earth. Which segment is the satellite part of?

space segment