Earth Science Applications of Space Based Geodesy

DES-7355

Tu-Th 9:40-11:05

Seminar Room in 3892 Central Ave. (Long building)

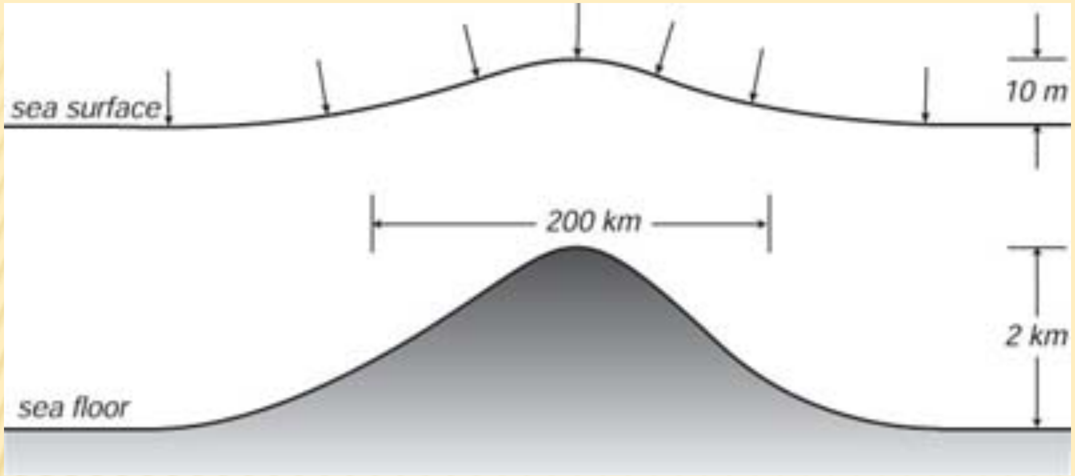
Bob Smalley
Office: 3892 Central Ave, Room 103
678-4929
Office Hours – Wed 14:00-16:00 or if I' m in my office.

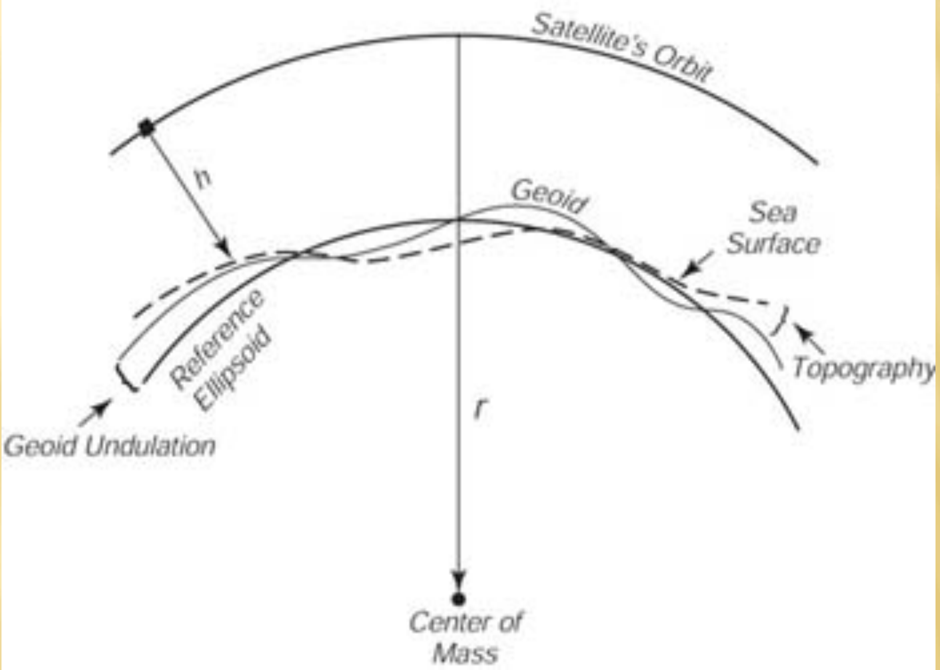
http://www.ceri.memphis.edu/people/smalley/ESCI7355/ESCI_7355_Applications_of_Space_Based_Geodesy.html

Class 4

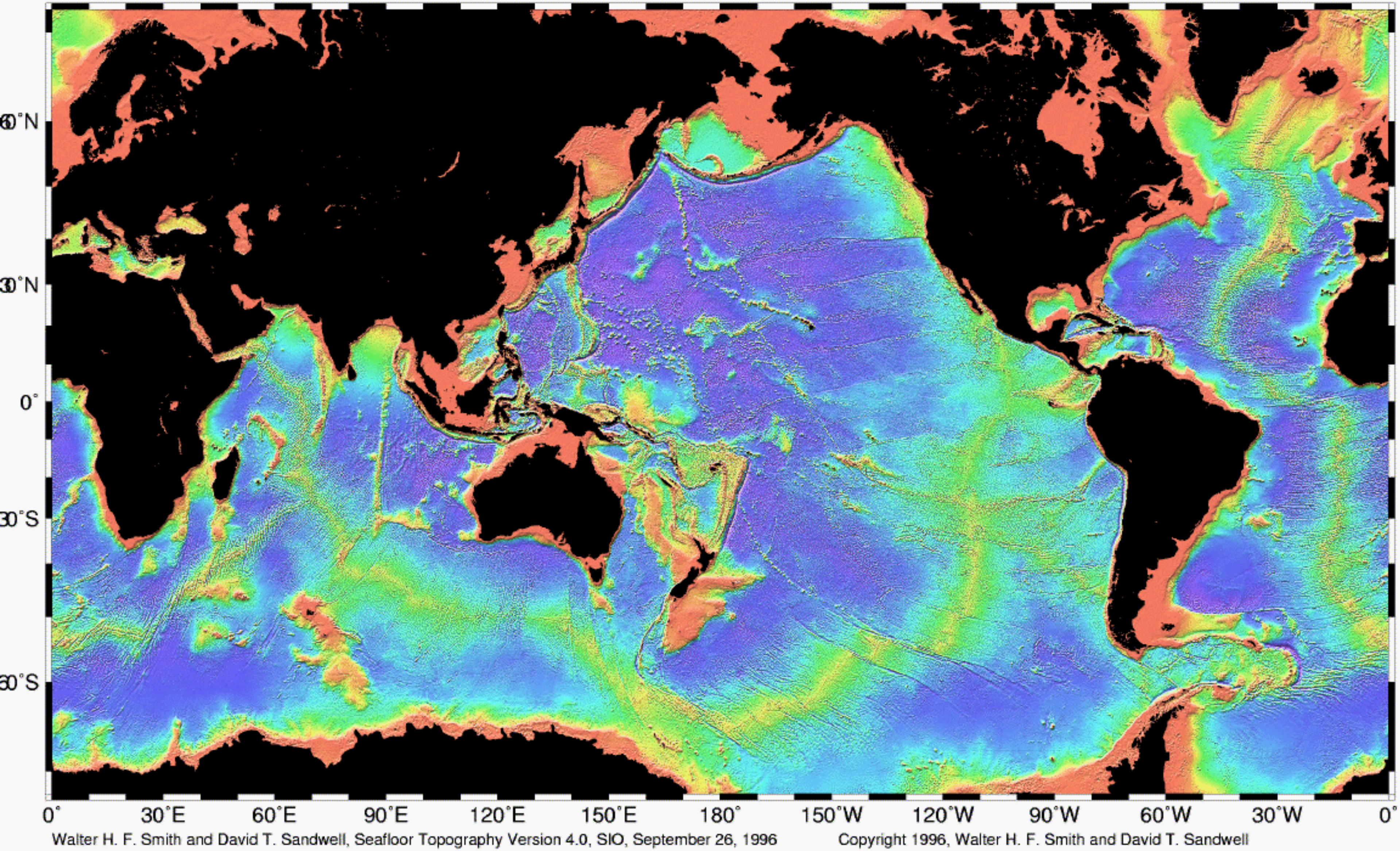
Go over homework

Go over big picture of homework



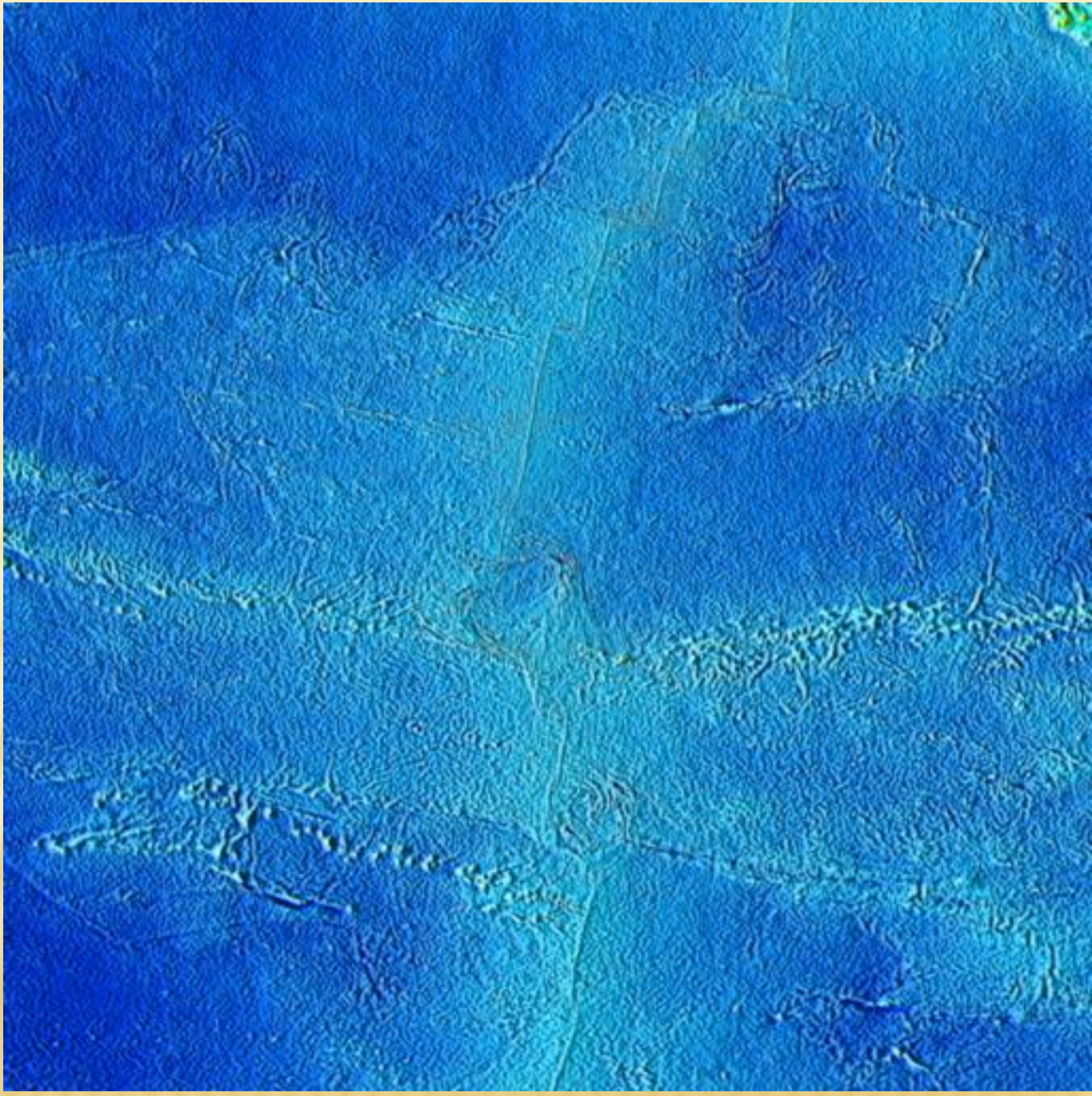


http://oceanworld.tamu.edu/resources/ocng_textbook/chapter03/chapter03_04.htm

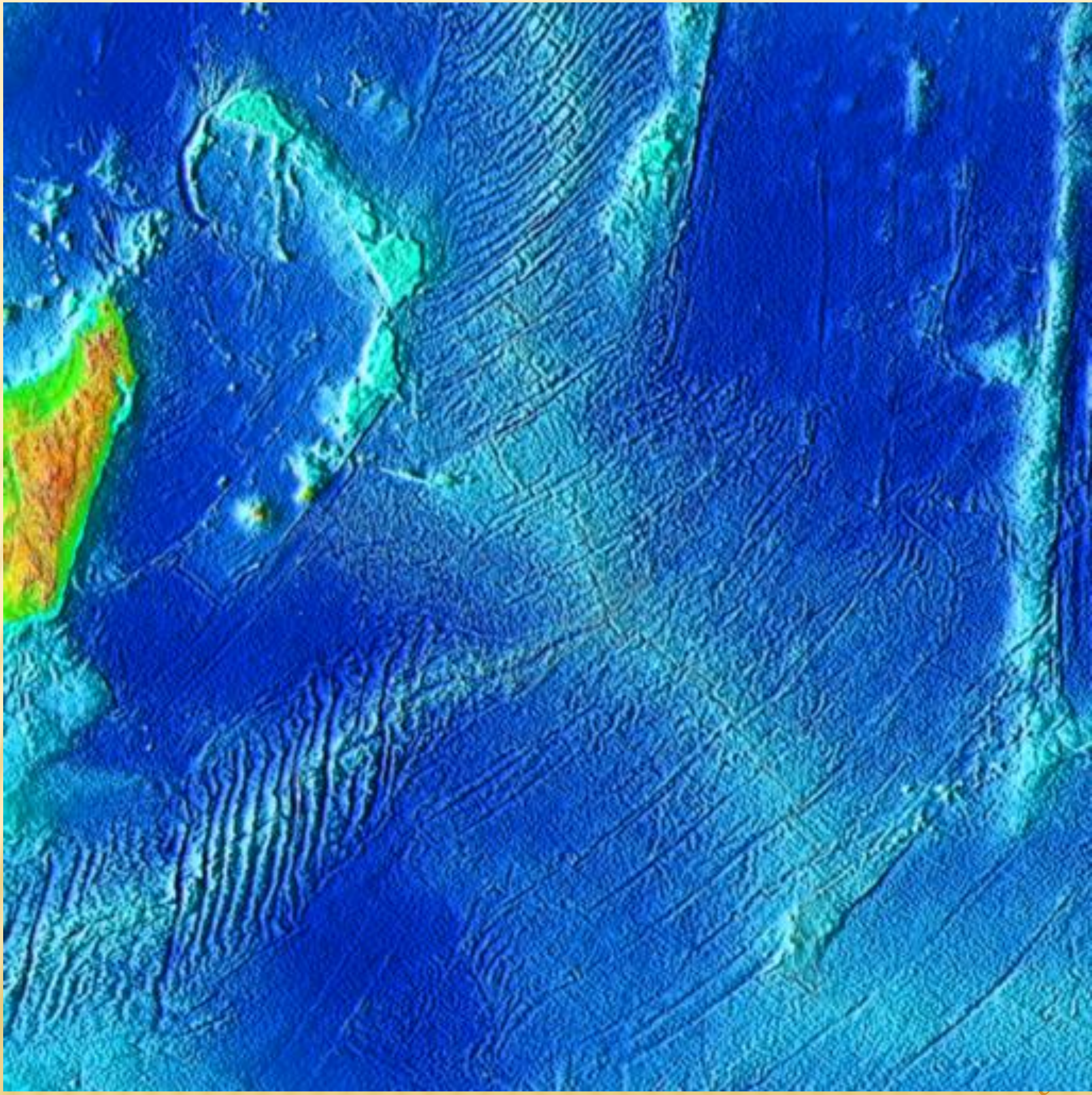


Predicted or Estimated topography from gravity (gravity is not topography, but they are related with some simple assumptions). Have to worry about things like isostatic compensation (EPR - fast spreading, hot and soft, is nearly isostatically compensated, so NO gravity signal - notice it is "fuzzy"). Can see dense structures (seamounts) completely buried in sediment! A 2000 m tall, 20 km diameter undersea volcano will produce a bump 2 m high and perhaps 40 km across (not visible to the naked eye!) Large scale, poorly understood density variations in the earth's crust, lithosphere and upper mantle cause 100 m undulations in the sea surface from the ellipsoid.

East Pacific Rise (EPR). Fast spreading ridge - hot. Topography isostatically compensated so "fuzzy", since "predicted" topography comes from gravity anomaly signal (gravity is NOT topography).



Indian Ocean. Lithosphere supports topography elastically (cold, strong when formed) rather than isostatically. Get gravity signal due to departure from isostacy.



FINALLY GPS

BRIEF HISTORY OF GPS

- Original concept developed around 1960
  - In the wake of Sputnik & Explorer
- Preliminary system, *Transit* (doppler based), operational in 1964
  - Developed for nuke submarines
  - 5 polar-orbiting satellites, Doppler measurements only
- *Timation* satellites, 1967-69, used the first onboard precise clock for passive ranging

A. Ganse, U. Washington , http://staff.washington.edu/aganse/

BRIEF HISTORY OF GPS

- Fullscale GPS development began in 1973
  - Renamed *Navstar*, but name never caught on
- First 4 SV's launched in 1978
- GPS IOC in December 1993 (FOC in April 1995)

In 1997, U.S. Secretary of Transportation Federico Pena stated, "Most people don't know what GPS is.

Five years from now, Americans won't know how we lived without it."

Today, Global Positioning System in included as part of in-vehicle navigation systems and cellular phones.

It's taken a few more than five years but the rate of Global Positioning System use will continue to explode.

GPS

- Transit improved by increasing constellation size + improving accuracy ➔ GPS NAVSTAR
  - Navigation System with Timing And Ranging

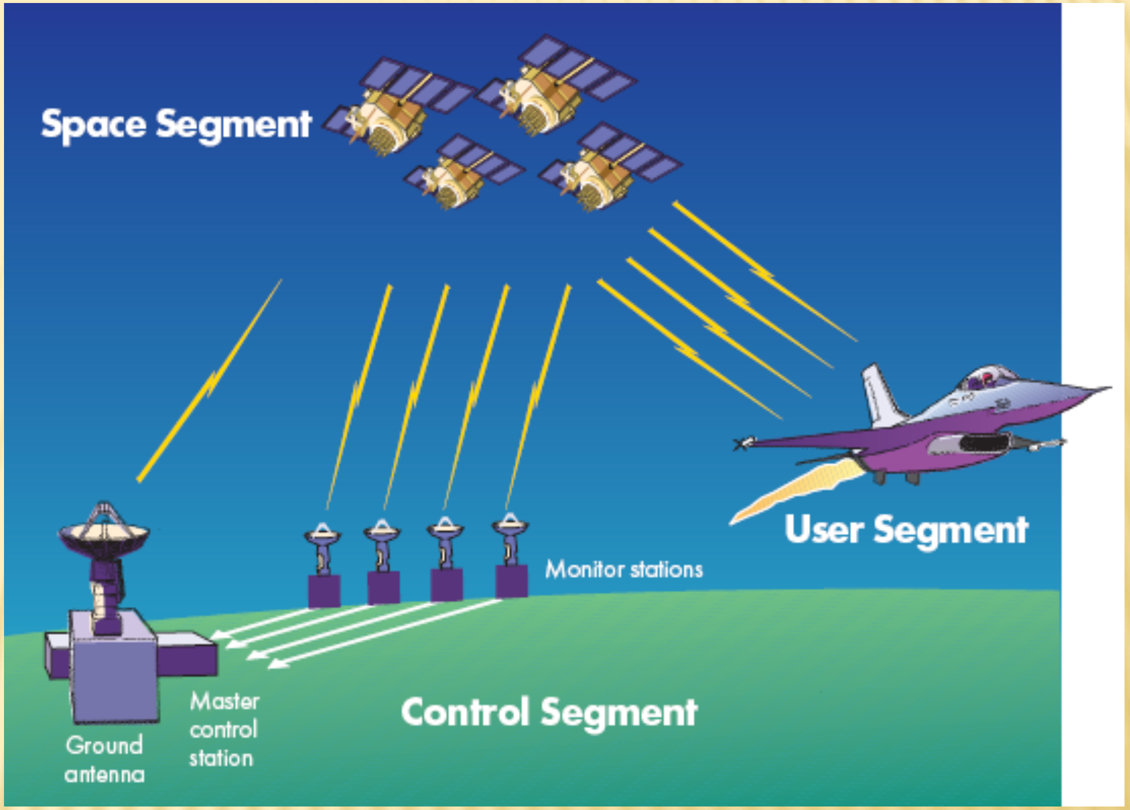
- GPS enabled by:
  - Stable platforms in predictable orbits
    - So station locations are highly predictable
  - Ultra-stable clocks onboard
    - Time-synchronization feasible ➔ can use trilateration
  - Spread spectrum signaling
    - Use CDMA to access multiple transmitters at once
  - Low-cost integrated circuits
    - Trades cheaper receiver clock for more processing

GPS TIDBITS

- Development costs estimate ~$12 billion

- Annual operating cost ~$400 million

GPS Tidbits



- 3 Segments:
  - Space: Satellites
  - User: Receivers
  - Control: Monitor & Control stations

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GPS TIDBITS

- Prime Space Segment contractor: Rockwell International

- Coordinate Reference: WGS-84 ECEF

- Operated by US Air Force Space Command (AFSC)
  - Mission control center operations at Schriever (formerly Falcon) AFB, Colorado Springs

WHO USES IT?

- Everyone!
- Merchant, Navy, Coast Guard vessels
  - Forget about the sextant, Loran, etc.
- Commercial Airliners, Civil Pilots
- Surveyors
  - Has completely revolutionized surveying
- Commercial Truckers
- Hikers, Mountain Climbers, Backpackers
- Cars
- Communications and Imaging Satellites
  - Space-to-Space Navigation
- Any system requiring accurate timing

WHO USES IT?

- GEOPHYSICICISTS and GEODESISTS

(not even mentioned on previous slide by Ganse!)

Basics of Navigation

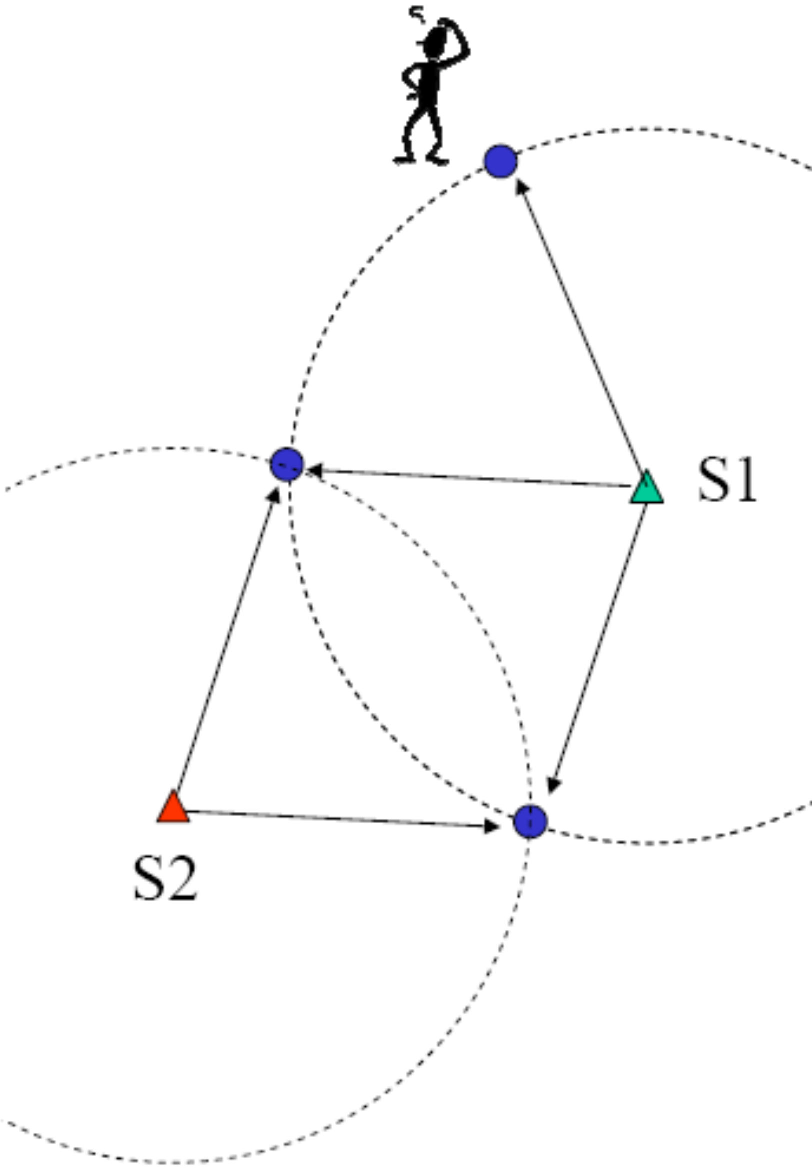
- Goal: determine our location relative to a known coordinate frame

- Basic approach:
  - Ultrasonic/laser distance meter
    - Range: 0.1 ft - 330ft (0.3m - 100m)
    - Accuracy: ±0.2in (5mm)
  - Measure **range** r_k to **known stations** (x_k, y_k) in the specified coordinate frame
  - In 2D: $r_k = \sqrt{(x_k - x)^2 + (y_k - y)^2} + v_k$

From J. HOW, MIT

2D Example Continued

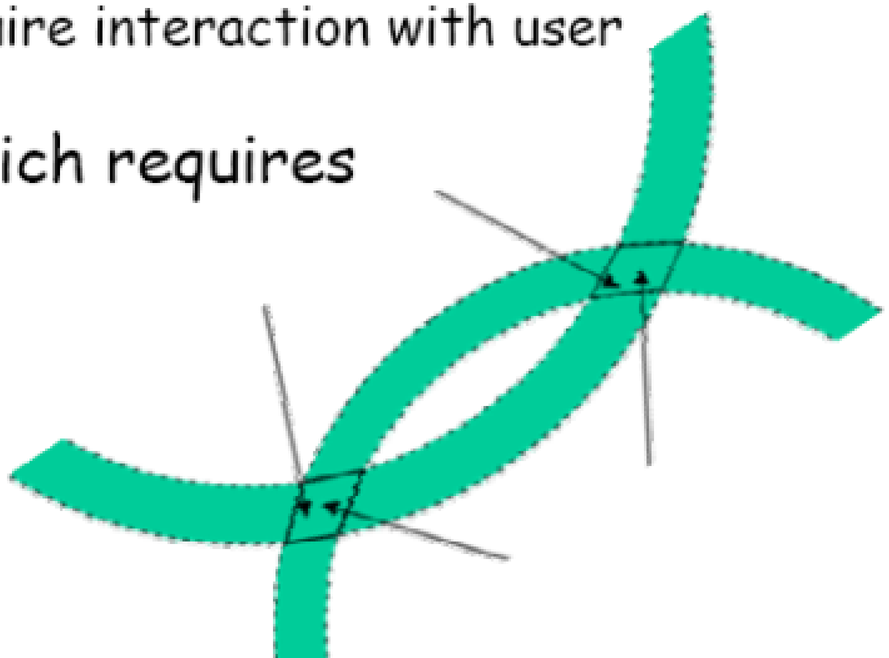
- Ranging to 1 station places us anywhere on a circle
- Ranging to 2 stations reduces uncertainty to only 2 points
- Could use a 3rd station to determine unique position estimate



From J. HOW, MIT

Basic Navigation

- Process called *trilateration* (triangulation based on circular constraints from the range)
  - Extends to 3D relatively easily, but requires stations "out of the plane" → explains why terrestrial navigation in 2D
- Describes an **active system**. Could use **passive system**
  - Transmitters at stations, user just receives a signal
  - Ideal for military, doesn't require interaction with user
- *Time-of-Arrival* system, which requires tight clock synchronization
  - 1μs error → 300m error
  - Better clock → higher cost



From J. HOW, MIT

GPS Timing

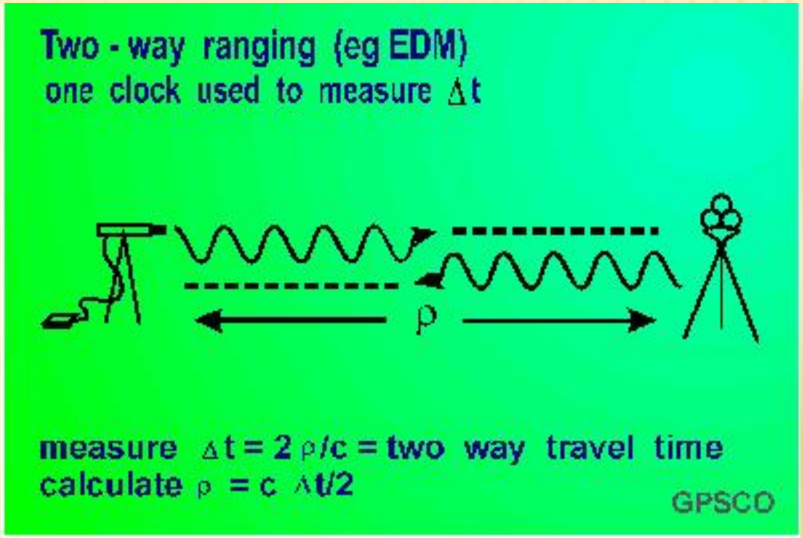
- Trilateration requires synchronized clocks:

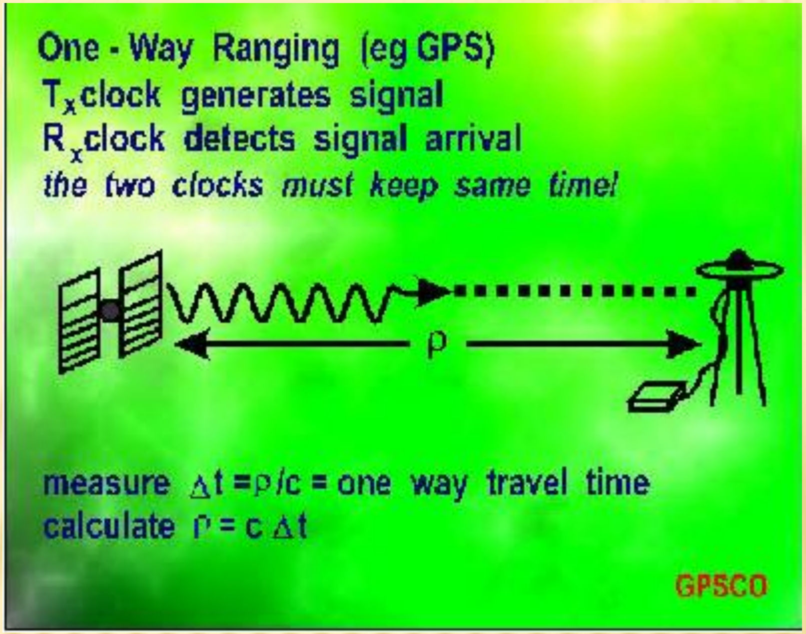
(Measured time of arrival) – (Time sent) = (Time of flight) → Range

- But requiring global synchronization of user & transmitter clocks would be very **cumbersome**
  - So GPS satellites use 4 oven-controlled atomic clocks
  - And to reduce cost, receiver uses low-cost crystal oscillator
    - Adds ***user clock error*** that is common to all measurements

- GPS design:
  - Transmitters are synchronized
  - They broadcast the time that the signals were sent

→ User clock error is a fourth variable that we must solve for in real-time (need 4 measurements)


Two - way ranging (eg EDM)
one clock used to measure Δt
ρ
measure Δt = 2 ρ/c = two way travel time
calculate ρ = c Δt/2
GPSCO


One - Way Ranging (eg GPS)
T_x clock generates signal
R_x clock detects signal arrival
the two clocks must keep same time!
ρ
measure $\Delta t = \rho / c$ = one way travel time
calculate $\rho = c\,\Delta t$
GPSCO

Advantages of One-Way Ranging

- Receiver doesn't have to generate signal, which means

•We can build inexpensive portable receivers

•Receiver cannot be located (targeted)

•Receiver cannot be charged

http://www.geology.buffalo.edu/courses/gly560/Lectures/GPS

Determining Range (Distance)

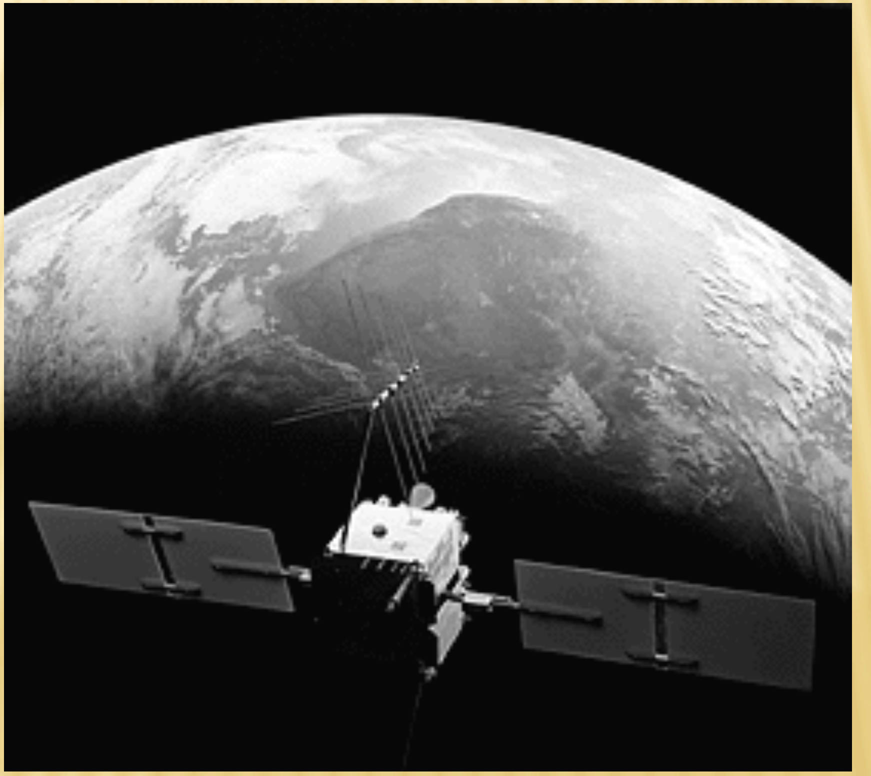
- Measure time it takes for radio signal to reach receiver, use speed of light to convert to distance.

- This requires
- Very good clocks
- Precise location of the satellite
- Signal processing over background

http://www.geology.buffalo.edu/courses/gly560/Lectures/GPS

we will break the process into five conceptual pieces

step 1: using satellite ranging
step 2: measuring distance from satellite
step 3: getting perfect timing
step 4: knowing where a satellite is in space
step 5: identifying errors



Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html

step 1: using satellite ranging

MULTI-SATELLITE RANGING

GPS is time of flight (range) system
(like locating earthquakes with P waves only)

step 1: using satellite ranging

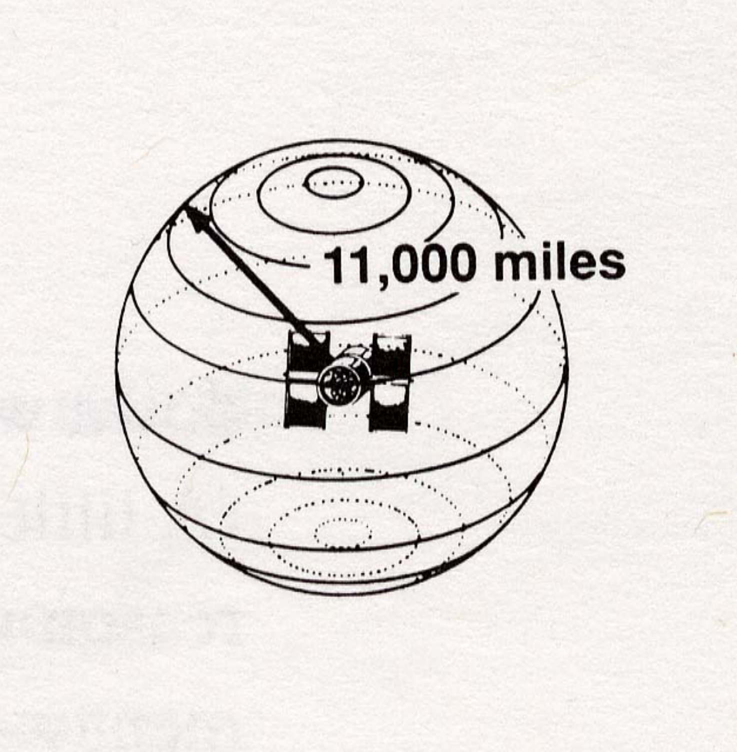
GPS is based on satellite ranging, i.e. distance from satelli

...satellites are precise reference points

...we determine our distance from them

we will assume for now we know exactly where satellite is and how far away from it we are...

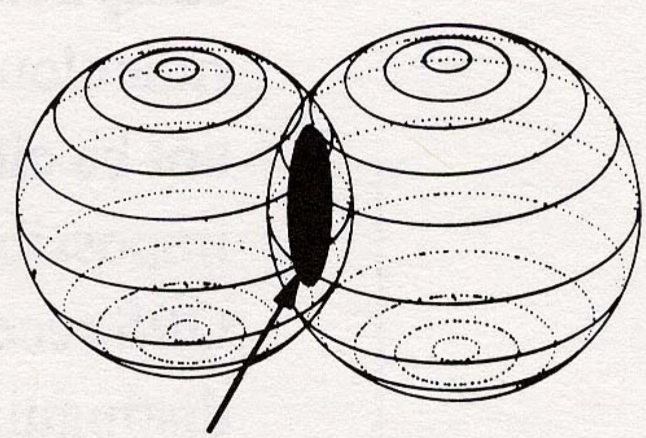
if we are lost and we know
that we are 11,000 miles
from satellite A...
we are somewhere on a sphere
whose middle is satellite A
and diameter is 11,000 miles



Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html and Trimble

step 1: using satellite ranging

if we also know that we are
12,000 miles from satellite B
...we can narrow down where
we must be...
only place in universe is on
circle where two spheres intersect



two measurements puts
us somewhere on this circle

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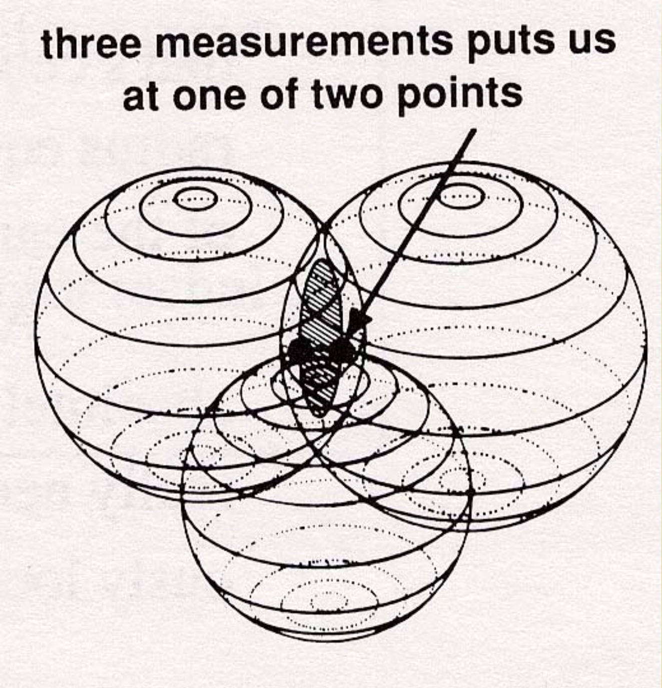
step 1: using satellite ranging

if we also know that we are 13,000 miles from satellite C ...our situation improves immensely... only place in universe is at either of two points where three spheres intersect



Which point you are at is determined by "sanity" – 1 point obviously wrong.

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step 1: using satellite ranging

three satellites can be enough to determine position...
one of the two points generally is not possible
(far off in space)

two satellites can be enough if you know your elevation
...why?

one of the spheres can be replaced with Earth...
...center of Earth is "satellite position"

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step 1: using satellite ranging

generally four are necessary

....why this is so a little later

And more is better

this is basic principle behind GPS...

...using satellites for trilaturation

step 2: measuring distance from satellite

because GPS based on knowing distance from satellite

...we need to have a method for determing how far away the satellites are

use velocity x time = distance

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step 2: measuring distance from satellite

GPS system works by timing how long it takes a radio signal
to reach the receiver from a satellite…

…distance is calculated from that time…

radio waves travel at speed of light: 300×10^6 m/second

problem: need to know when GPS satellite started sending its radio message

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requires very good clocks that measure short times…
…electromagnetic waves move very quickly

step 3: getting perfect timing

use atomic clocks

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step 3: getting perfect timing

atomic clocks

came into being during World War II

-physicists wanted to test Einstein' s ideas about gravity and time

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step 3: getting perfect timing

atomic clocks

- previous clocks relied on pendulums, spring mechanisms, crystal oscillators

- early atomic clocks looked at vibrations of quartz crystal

…keep time to < 1/1000th second per day

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step 3: getting perfect timing

atomic clocks

• early atomic clocks looked at vibrations of quartz crystal

...keep time to < 1/1000th second per day

..not accurate enough to assess affect of gravity on time

...Einstein predicted that clock on Mt. Everest would run 30 millionths of a second faster than clock at sea level

...needed to look at oscillations of atoms

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step 3: getting perfect timing

atomic clocks

principle behind atomic clocks...

atoms absorb or emit electomagnetic energy in discrete (quantized) amounts

corresponding to differences in energy between different
configurations of the atoms

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step 3: getting perfect timing

atomic clocks

principle behind atomic clocks…

when atom goes from a higher energy state to lower one, it emits an electromagnetic wave of characteristic frequency
…known as “resonant frequency”

these resonant frequencies are identical for every atom of a given type:

ex. - cesium 133 atoms: 9,192,631,770 hz

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step 3: getting perfect timing

atomic clocks

principle behind atomic clocks…

cesium can be used to create an extraordinarily precise clock

(can also use hydrogen and rubidium)

GPS satellite clocks are cesium and rubidium clocks

Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html and Trimble

step 3: getting perfect timing

electromagnetic energy travels at 300×10^6 m/second
...an error of 1/100th second leads to error of 3000 km.

how do we know that receiver and satellite are on same time?

satellites have atomic clocks (4 of them for redundancy)

...at $100,000 apiece, they are not in receivers!

receivers have “ordinary” clocks
(otherwise receivers would cost > $100K)

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step 3: getting perfect timing

...can get around this (bad clock) by having an "extra" measurement

...hence 4 satellites are necessary

three perfect time measurements will lead to unique (not quite), solution [(x,y,z) or (lat, lon, elevation)]

....four imperfect time measurements also will lead to correct solution [(x,y,z,δt) or (lat, lon, elevation,δt)]

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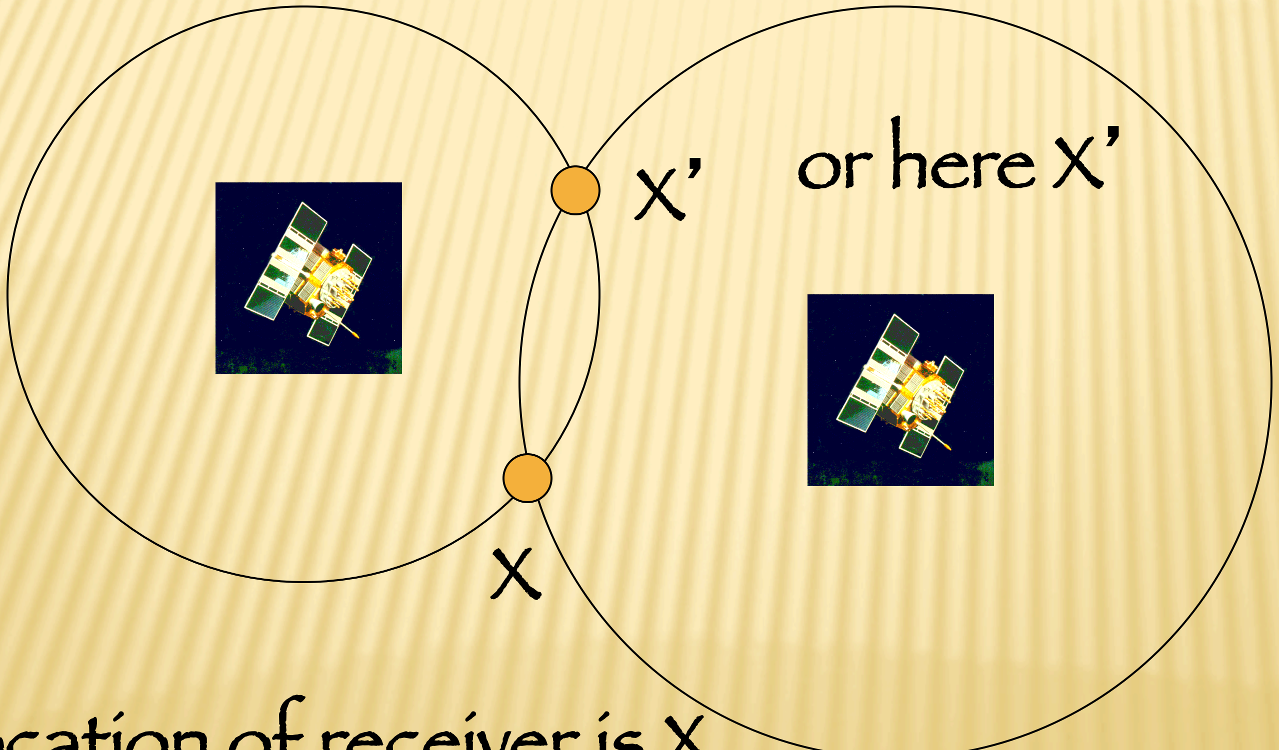
illustrate this in 2D...

instead of referring to satellite range in distance,
...we will use time units

two satellites: first at distance of 4 seconds
second at distance of 6 seconds



this is if clocks were correct...

what if they weren't correct?

location of receiver is X

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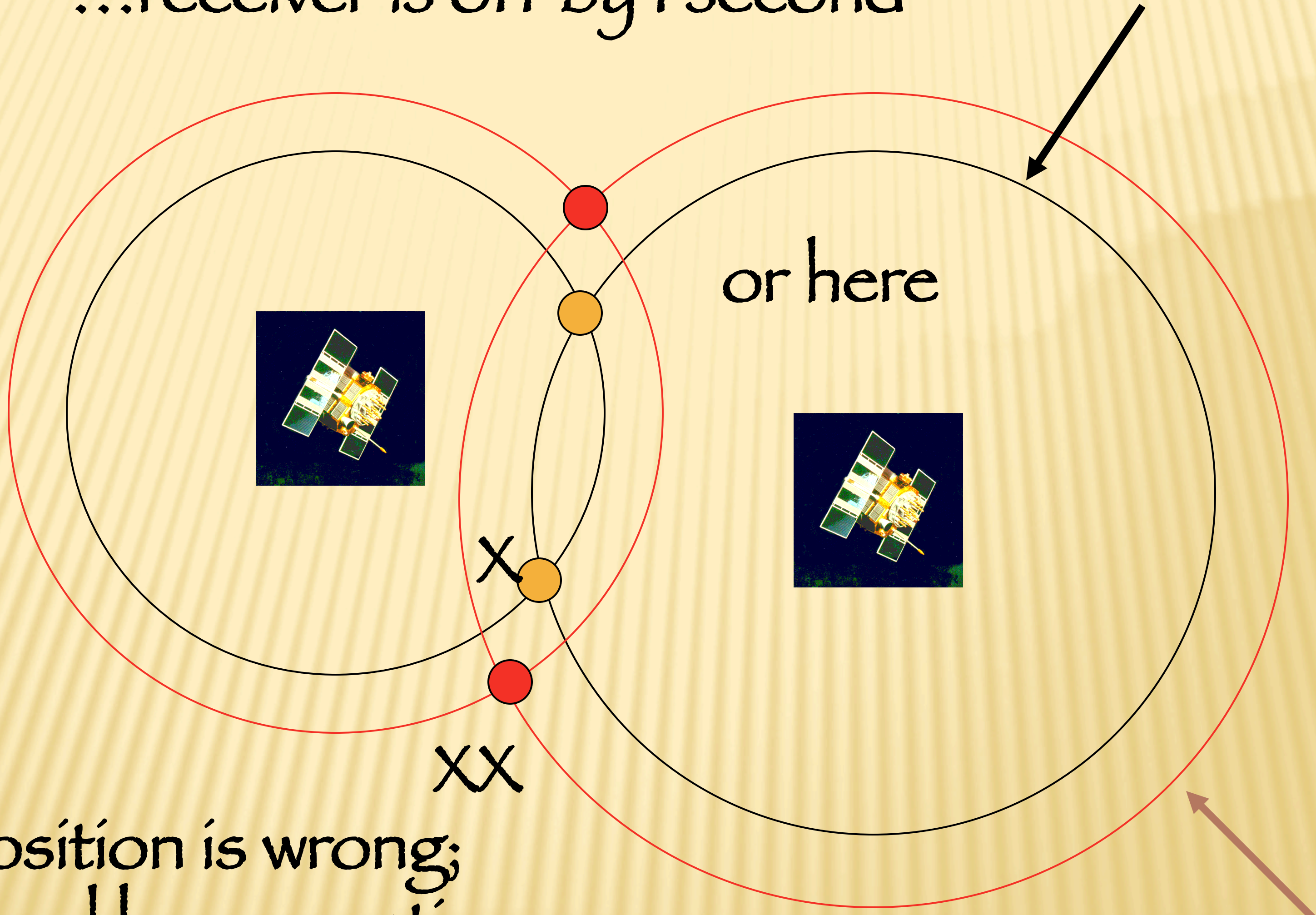
what if receiver wasn't perfect?
...receiver is off by 1 second

"correct" time



wrong time

XX position is wrong;
caused by wrong time
measurements

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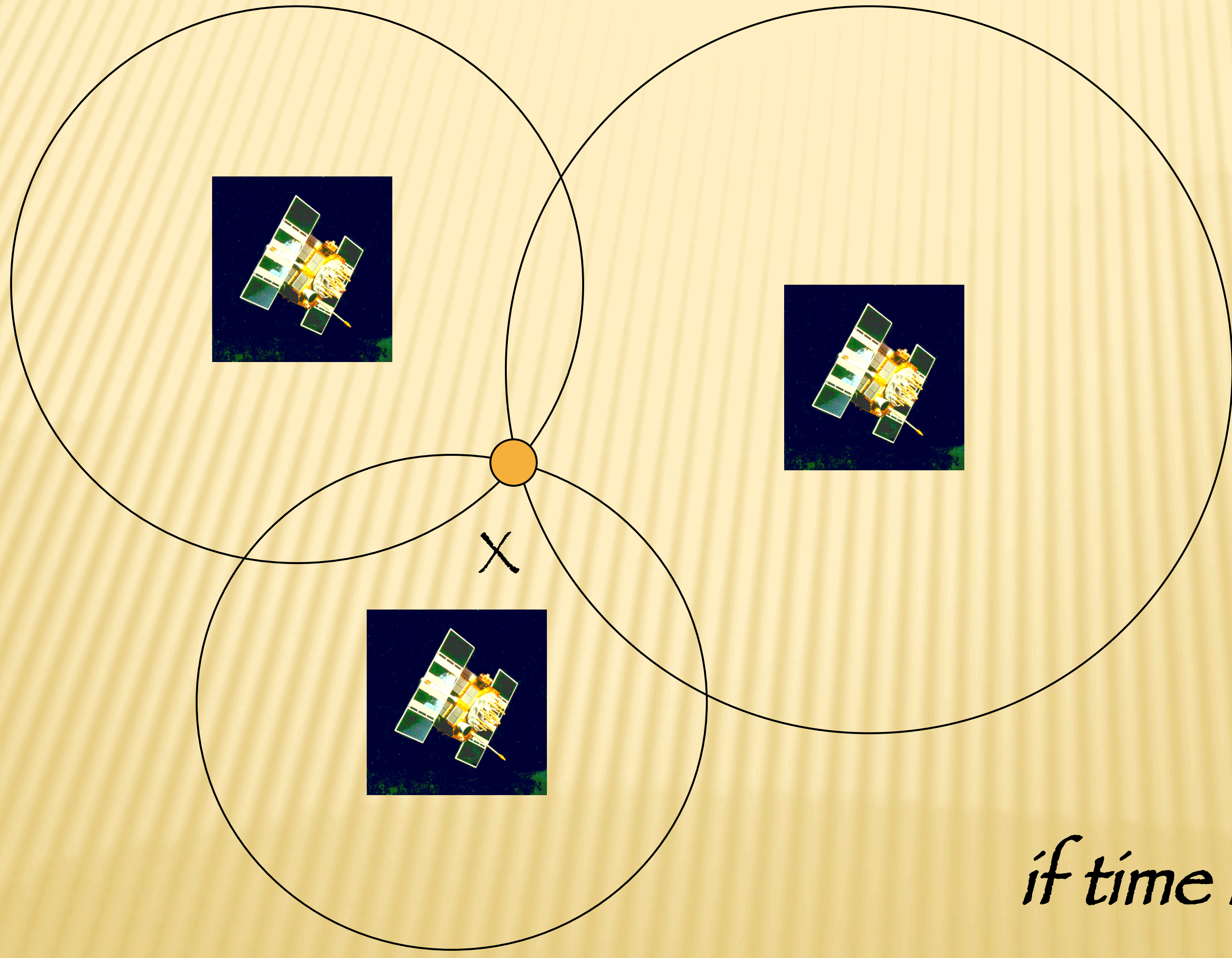
how do we know that it is wrong?

...measurement from third satellite (fourth in 3D)

Add a 3rd satellite at 3 seconds



Circles from all 3 intersect at X...

if time is correct

This also solves the uniqueness problem

if time is not correct...

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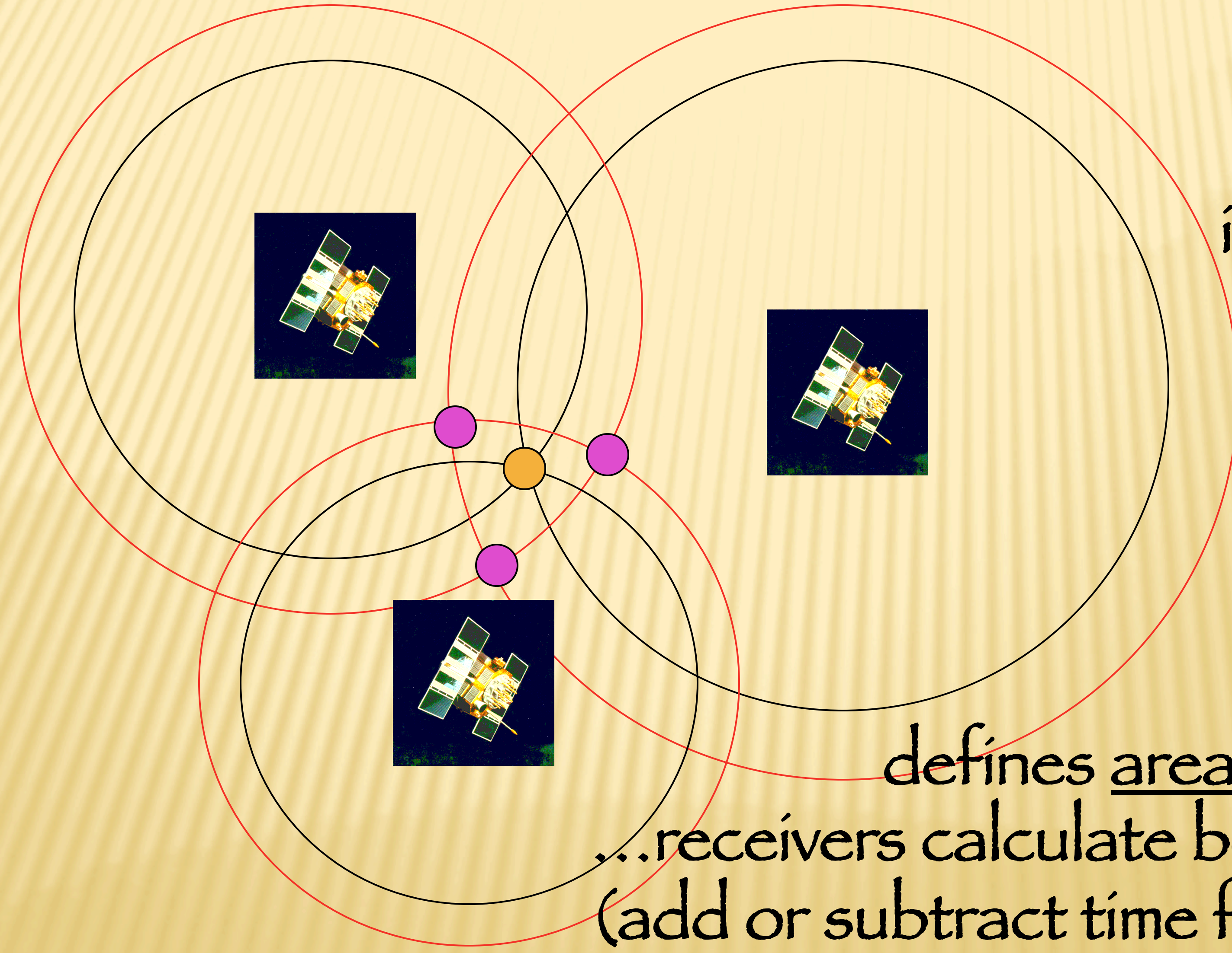
add our one second error to the third receiver…

…circle from 3rd SV does not intersect where other 2 do



purple dots
are
intersections
of circles
from2 SVs

defines area of solutions

…receivers calculate best solution

(add or subtract time from each SV)

Aside –

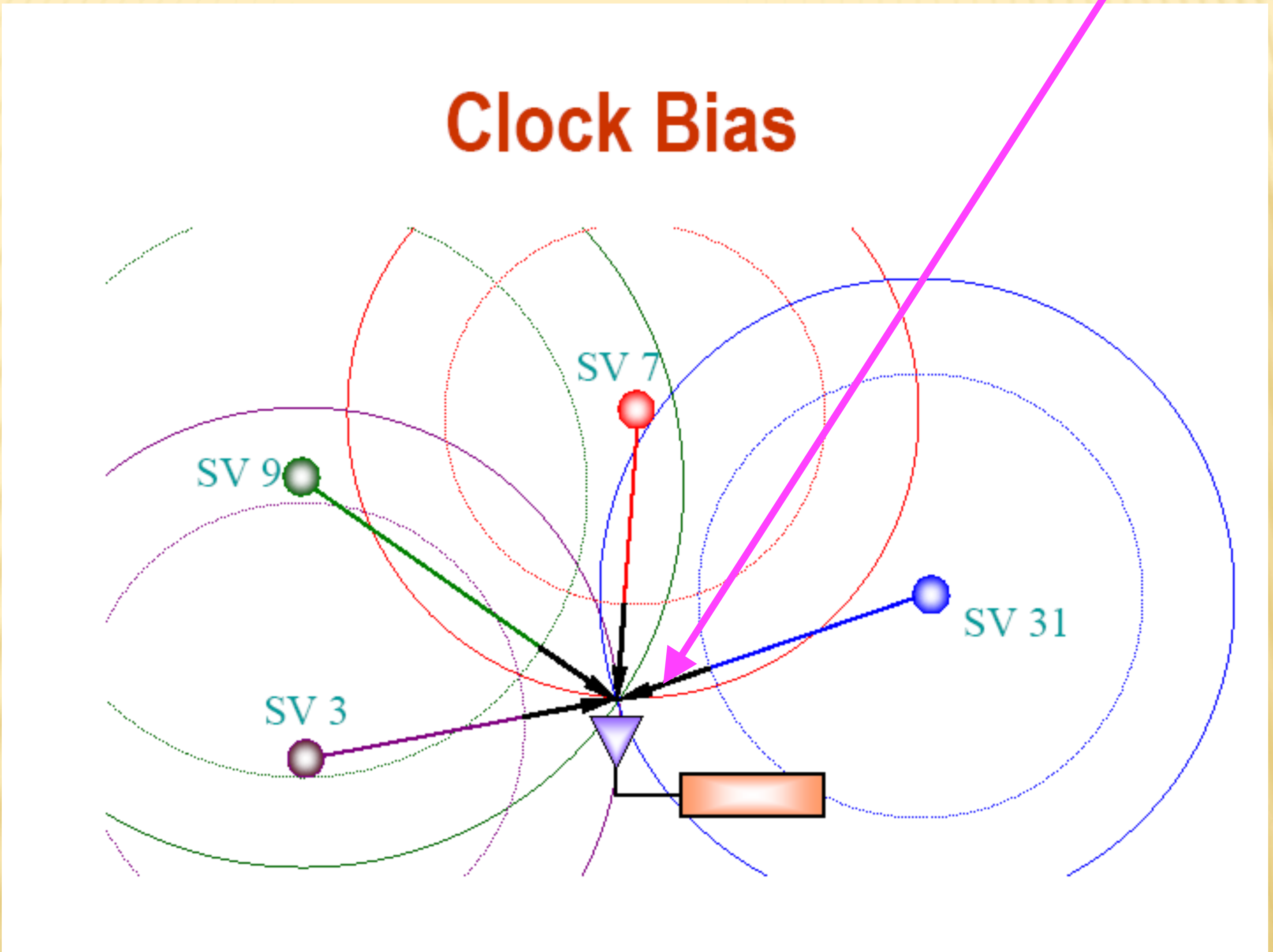
LORAN also transmits time synchronized, identifiable signals

therefore

One can locate oneself (in 2-D) using the same techniques as GPS using 3 or more LORAN signals

(they do not all have to be in the same "chain")

Fourth satellite allows calculation of clock bias



http://www.unav-micro.com/about_gps.htm

step 3: getting perfect timing

now that we have precise clocks...
...how do we know when the signals left the satellite?

this is where the designers of GPS were clever...
...synchronize satellite and receiver so
they are generating same code at same time

We will look at this in more detail later

Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html and Trimble

finally…
step 4: knowing where a satellite is in space

Satellites in known orbits.

Orbits programmed into receivers.

Satellites constantly monitored by DoD
…identify errors (ephemeris errors) in orbits
…usually minor.

Corrections relayed back to satellite.

Satellite transmits actual orbit information.

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step 4: knowing where a satellite is in space

Orbital data (ephemeris) is embedded in the satellite data message

Ephemeris data contains parameters that describe the elliptical path of the satellite

Receiver uses this data to calculate the position of the satellite (x,y,z)

http://www.unav-micro.com/about_gps.htm

Need 6 terms to define shape and orientation of ellipse

a – semi major axis

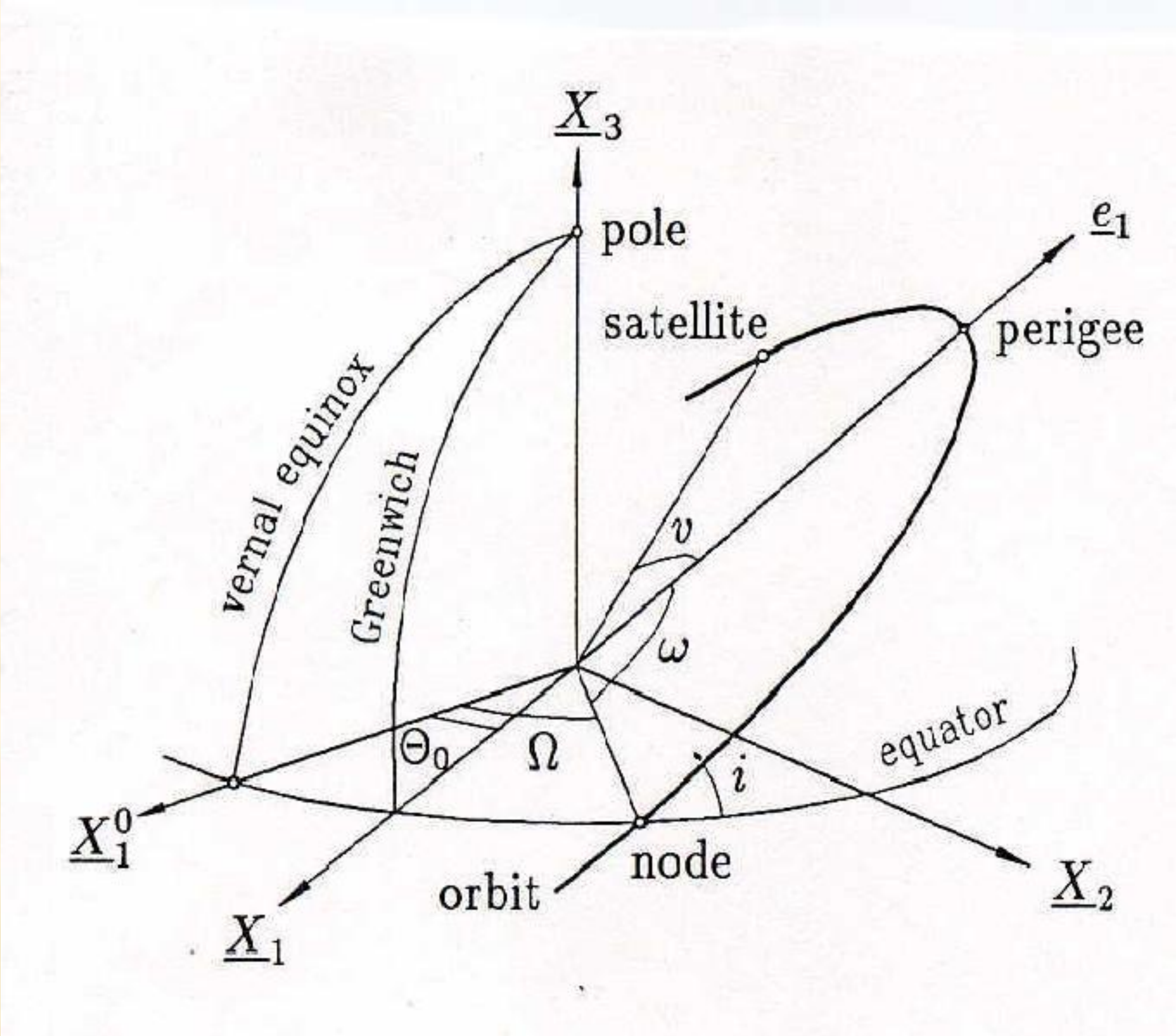
e – ecentricity

Ω – longitude ascending node

i – inclination

ω – argument of perigee

ν – true anomaly



http://www.colorado.edu/engineering/ASEN/asen5090/asen5090.html

step 5: identifying errors

Will do later

THE GPS CONSTELLATION

- 24 operational space vehicles ("SV' s")
  - 6 orbit planes, 4 SV' s/Plane
  - Plus at least 3 in-orbit spares
- Orbit characteristics:
  - Altitude: 20,180 km (SMA = 26558 km)
  - Inclination: 55°

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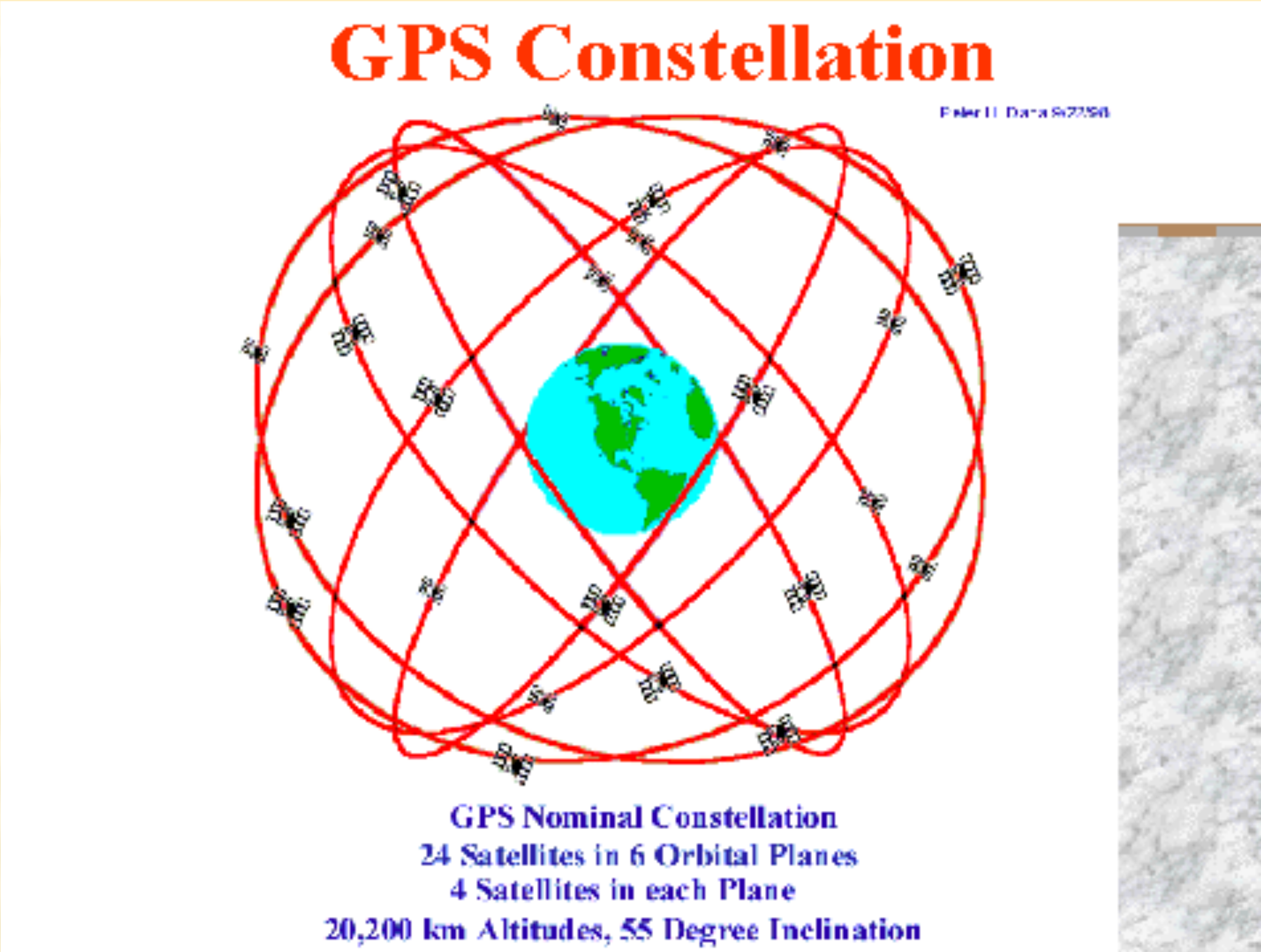

Simulation: GPS and GLONASS Simulation

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THE GPS CONSTELLATION

- More Orbit characteristics:
  - Eccentriciy: < 0.02 (nominally circular)
  - Nodal Regression: -0.004°/day (westward)
- The altitude results in an orbital period of 12 sidereal hours, thus SV's perform full revs 2/day.
- Period and regression lead to *repeating ground tracks*, i.e. each SV covers same "swath" on earth ~ 1/day.

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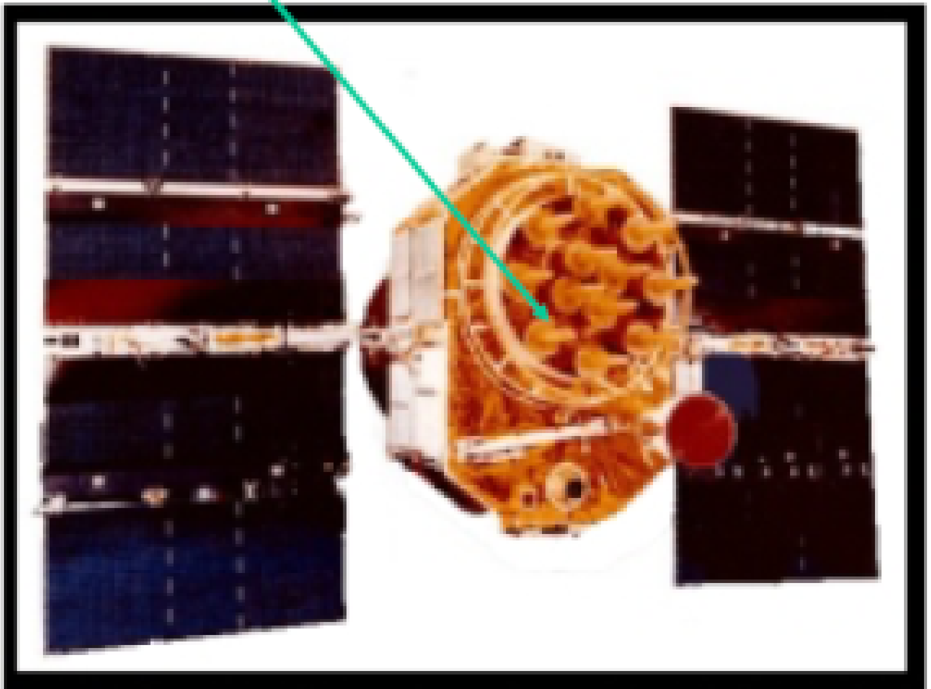
Navstar Satellite



Block IIA Satellite

- **Block I** - Initial evaluation
  - 845 kg / 4.5 year design life
  - Launched 1978 - 85
- **Block II** - 63° to 55° inclination
  - Weight ~ 1500 kg / 7.5yrs
  - Restricted signals
- **Block IIA** - *Advanced satellites* (minor improvements)
- **Block IIR** - "Replenishment"
  - 2000 kg / 7.8 year life
  - Designed to operate for 14 days without ground contact
  - Can range and cross-link between themselves

From J. HOW, MIT

GPS VISIBILITY

- GPS constellation is such that between 5 and 8 SV' s are visible from any point on earth
- Each SV tracked by a receiver is assigned a *channel*
- Good receivers are > 4-channel (track more than 4 SV' s)
  - Often as many as 12-channels in good receivers
  - Extra SV' s enable smooth handoffs & better solutions

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GPS VISIBILITY

- Which SV's are used for a solution is a function of geometry
  - *GDOP*: Geometric Dilution of Precision
    - Magnification of errors due to poor user/SV geometry
  - Good receivers compute GDOP and choose "best" SV's

TIMING

- Accuracy of position is only as good as your clock
  - To know where you are, you must know when you are
  - Receiver clock must match SV clock to compute delta-T

TIMING

- SVs carry atomic oscillators (2 rubidium, 2 cesium each)
  - Not practical for hand-held receiver

TIMING

- Accumulated drift of receiver clock is called clock *bias*
- The erroneously measured range is called a *pseudorange*
- To eliminate the bias, a 4th SV is tracked
  - 4 equations, 4 unknowns
  - Solution now generates X,Y,Z and b ("bias", is δt).
- If Doppler also tracked, Velocity can be computed

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GPS Time

GPS time is referenced to 6 January 1980, 00:00:00

GPS uses a week/time-into-week format

Jan 6 = First Sunday in 1980

GPS Time

GPS satellite clocks are essentially synched to *International Atomic Time (TAI)* (and therefore to UTC)

Ensemble of atomic clocks which provide international timing standards.

TAI is the basis for Coordinated Universal Time (UTC), used for most civil timekeeping

GPS time = TAI - 16s

Since 16 positive leap seconds since 1/6/1980
(last leap second 30 Jun, 2012)

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GPS Time

GPS time is different than GMT because GMT is continuously adjusted for Earth rotation and translation charges with respect to the sun and other celestial reference bodies.

GPS time shifts with respect to UTC as UTCis adjusted using positive or negative "leap" seconds to accommodate earth' s slowing, etc.

GPS time is not adjusted for celestial phenomena since it is based on the behavior of atomic clocks monitoring the satellite system.

Mod from - A. Ganse, U. Washington , http://staff.washington.edu/aganse/, http://www.eomonline.com/Common/Archives/1996jan/96jan_gps.html

More About Time

GPS system time referenced to Master USNO Clock, but now implements its own "composite clock"

SV clocks good to about 1 part in 10^{13}

Delta between GPS SV time & UTC is included in nav/timing message

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More About Time

Correction terms permit user to determine UTC to better than 90 nanoseconds (~10^{-7} sec)

The most effective time transfer mechanism anywhere

More About Time

Satellite velocity induces special relativistic time dilation of about -7.2 μsec/day

General relativistic gravitational frequency shift causes about 45.6 μsec/day

For a total 38.4 μsec/day

GPS clocks tuned to 10.22999999545 Mhz

(1 μsec -> 300 m, build up 1 μsec in 38 minutes if don' t correct!)

A. Ganse, U. Washington , http://staff.washington.edu/aganse/, Klein thesis ch 3

More About Time

The 10-bit GPS-week field in the data "rolled-over" on August 21/22 1999 – some receivers probably failed!