Current Directions in Navigation Technology

Symposium on the History and Future of Celestial Navigation
Mystic Seaport, CT
Nov 3-5, 2017

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Outline of Talk

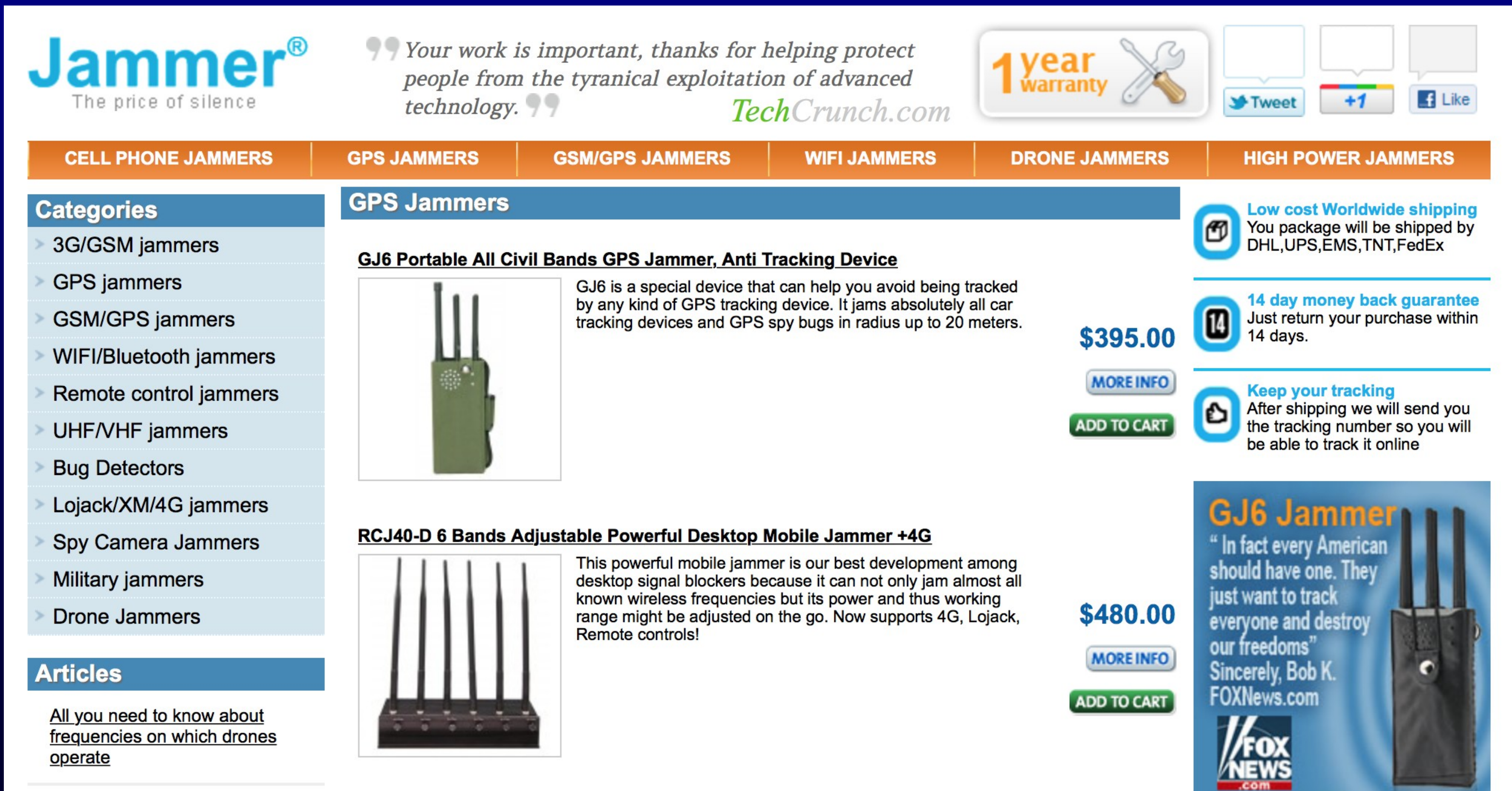
- Why we need alternatives to GPS
- Is there a GPS backup system in the future?
- Why celestial is still in the game
- A coloring-book history of automated celestial systems
- A basic challenge in automating celestial navigation

Limitations/Concerns About GPS

- Relatively weak signal, easily jammable
- GPS spoofing (civilian vulnerability)
- Sometimes not available or reliable in steep valleys or "urban canyons" (signal blockage and multi-path problems)
- Possible solar maximum problems
- No reliable indoor capability
- Concerns about a single point of failure in a rapidly evolving warfighting environment, which may include EMP, anti-satellite actions, and cyber warfare

Note: Omega, Transit, and U.S. LORAN are gone

GPS Jammers are Readily Available!



GPS Jammers are Readily Available!

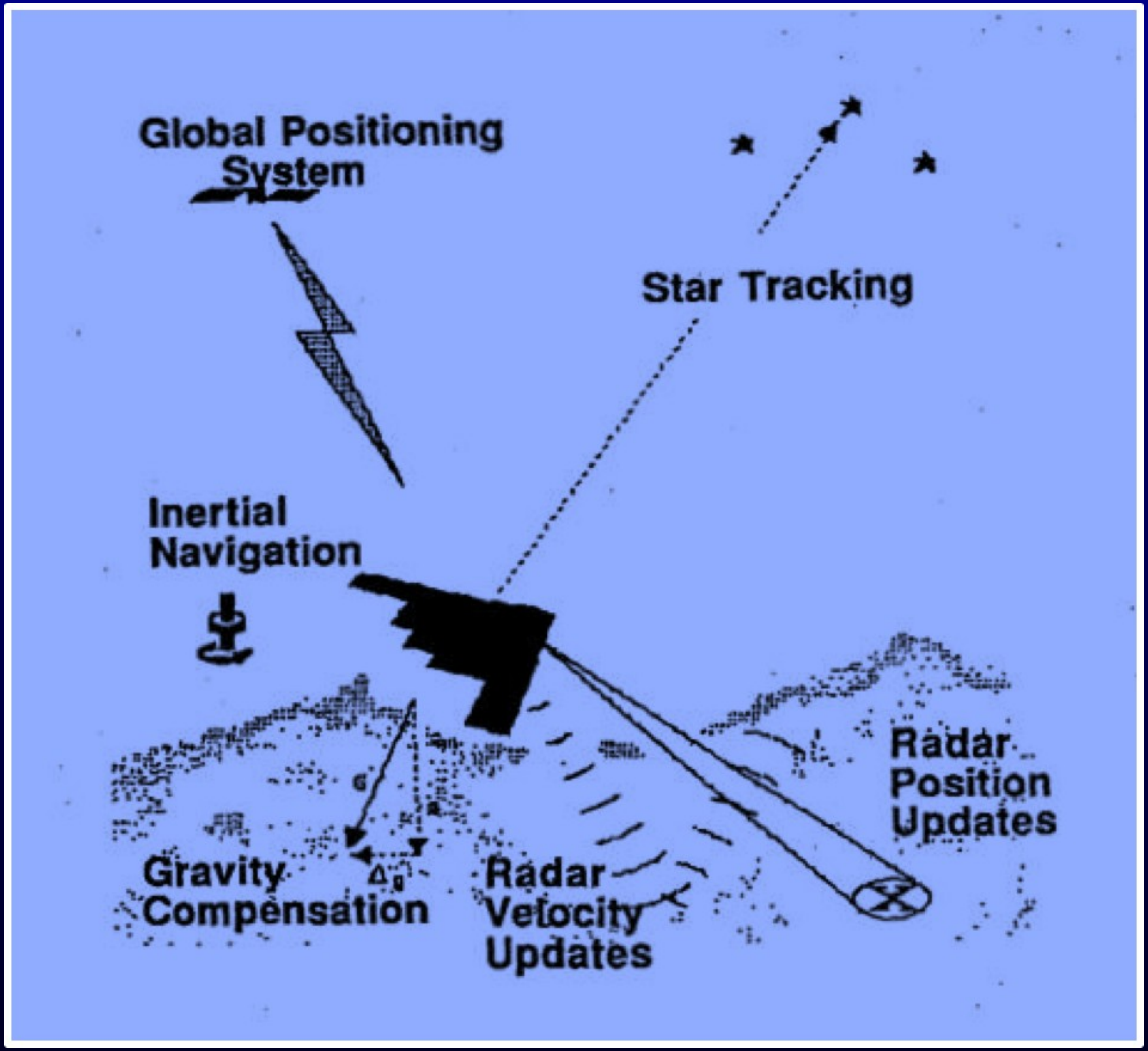
Modern Nav Solutions for Military Operations (1)

- Strengthen GPS
  - alternative frequencies/signals
  - "spot beam" for M code (military signal)
  - directional antennas on user side
  - better signal processing algorithms
- Combine GPS with inertial navigation systems (INS) to provide a nav "flywheel" that can bridge GPS outages
- Reprogrammed Iridium satellites
- Pseudolites

Modern Nav Solutions for Military Operations (2)

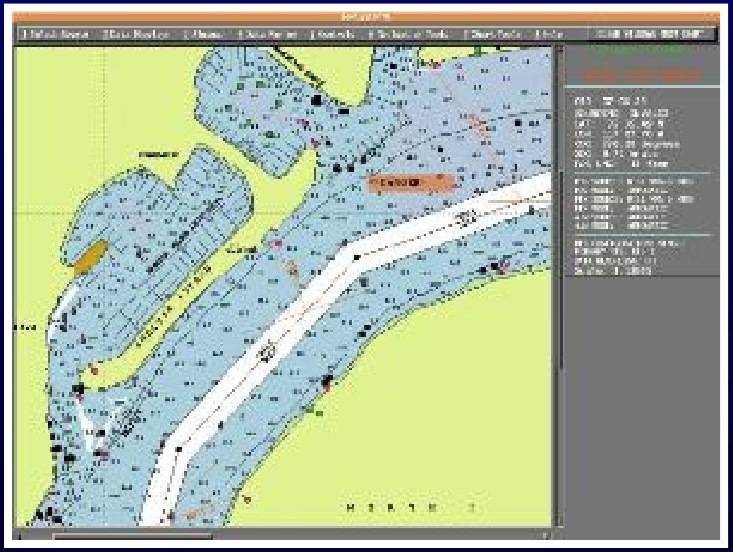
- Use blended-nav solutions using a variety of sensors
  - GPS
  - INS
  - bathymetry
  - altimetry
  - radar doppler
  - magnetic or gravitational field mapping/sensing
  - celestial
  - automated visual systems/ground feature recognition
  - use of radio signals of opportunity (civilian radio and TV broadcasts, air traffic control, non-US LORAN, etc.)
- Future US backup system for GPS (?)

A Modern Nav Solution for the B2



The Navy Appoach: NAVSSI

- NAVigation Sensor System Interface
- A shipboard computer system that combines navigation information from various sensors with digital nautical charts
- Provides a single shipwide navigation data source



… Soon to be replaced by **GPNTS**

GPS Backup for the US is Under Study (Again)

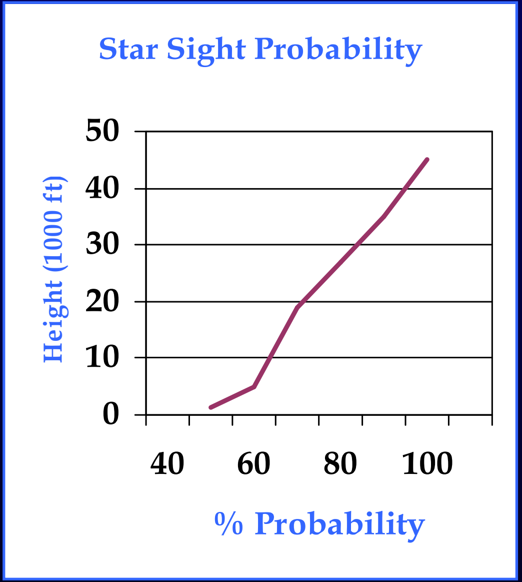
- Study committee formed by DHS
- Considering all uses of GPS, both civilian and military, for both position and time
- A new LORAN system, "Enhanced LORAN" (eLORAN), was moving forward in 2008 (and may still be the favored solution)
  - DHS spent $160 million in upgrades to old US LORAN-C sites
  - But political and budgetary issues intervened, so that…
  - Now, the old LORAN sites have been decommissioned and equipment is mostly gone

"Efforts to set up a GPS backup remain mired in studies"

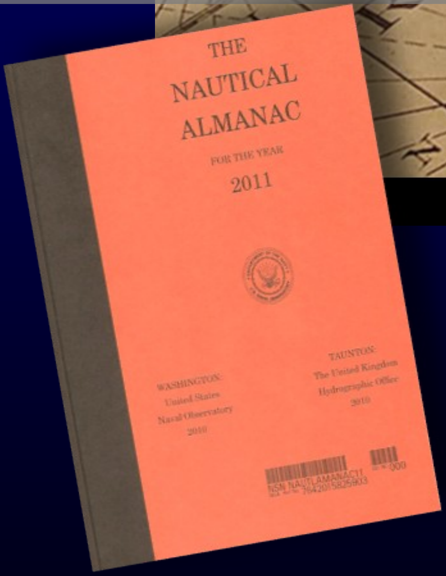
— *Inside GNSS*, May/June 2017

Why is Celestial Still in the Game?

- Passive
- World-wide
- Referred to a well-defined inertial coordinate system
- No external infrastructure to maintain
- Provides absolute attitude
- Yes, there are clouds and haze… but we can
  - Observe in the near IR
  - Use it at altitudes above most of the clouds
  - Use it as needed only to stabilize an INS nav solution



Celestial Nav – What We Usually Think of



Automated Celestial Nav — Beginnings

Started with the Snark jet-powered cruise missile in the 1950s

Automated Celestial Nav — on ICBMs

Continued with ICBM guidance systems:
Polaris, Trident, Minuteman, MX

(also Soviet missiles)

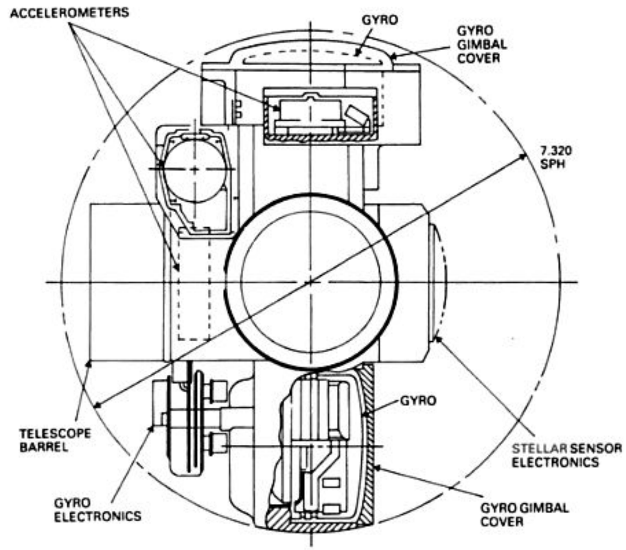


Figure 5.2
American "Paradigm" Design for Ballistic Missile Stellar-inertial Guidance System
Source: Redrawn from figure in Stephen F. Rounds and George Marmar "Stellar-Inertial Capabilities for Advanced ICBM," paper 83–2297 read to American Institute of Aeronautics and Astronautics 1983 Guidance and Control Conference.

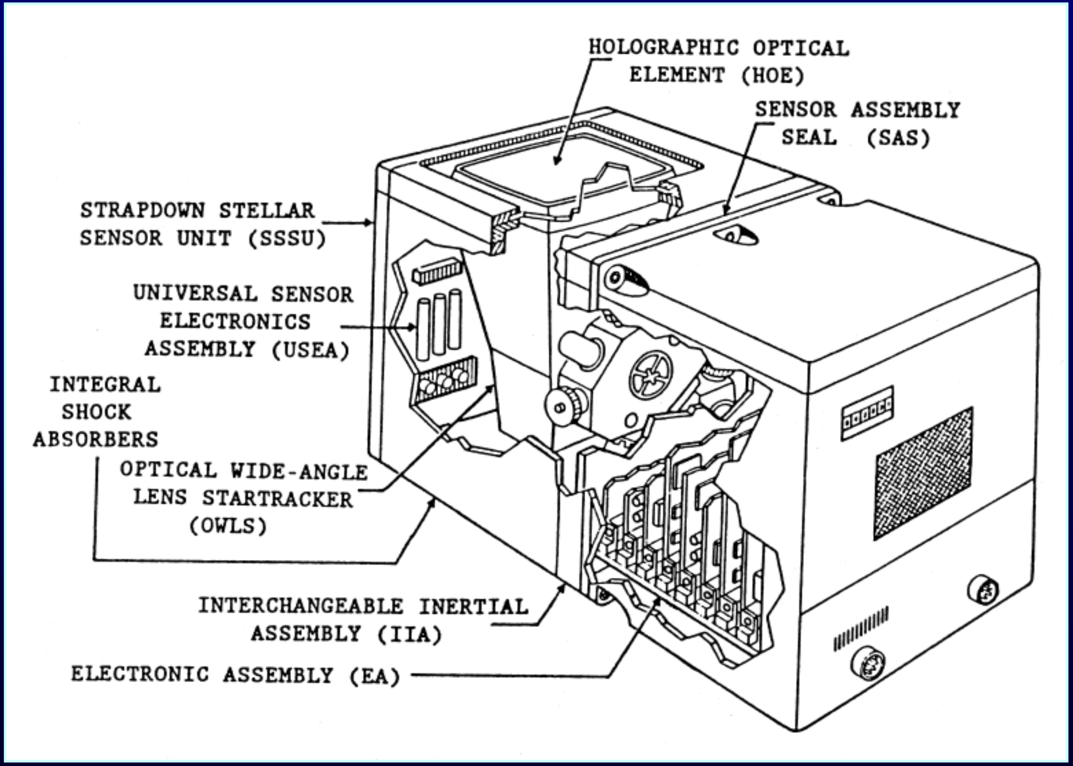
Drove a major mission area at USNO: improved absolute star positions for use in these systems

Automated Celestial Nav — on Aircraft

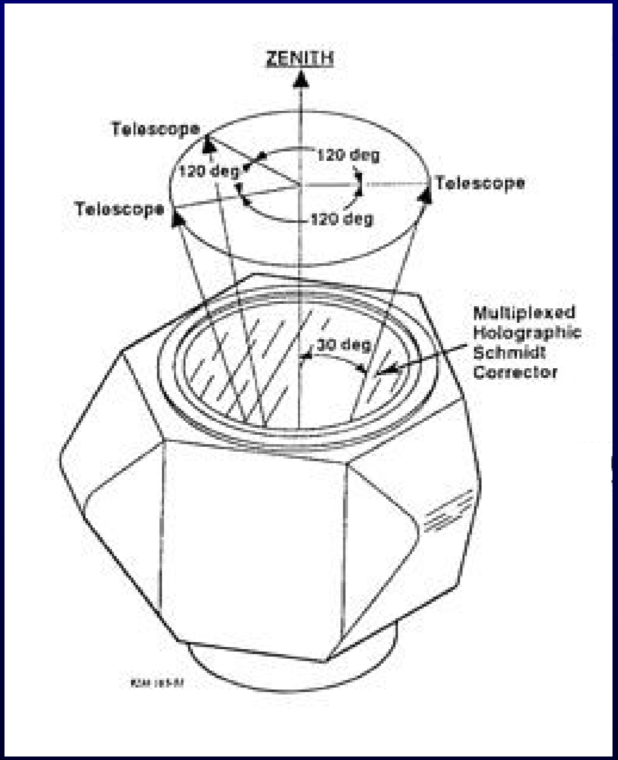
Aircraft systems: SR-71, RC-135, B2

Automated Celestial Nav — Experimental Aircraft Systems (Never Deployed)

Northrop OWLS

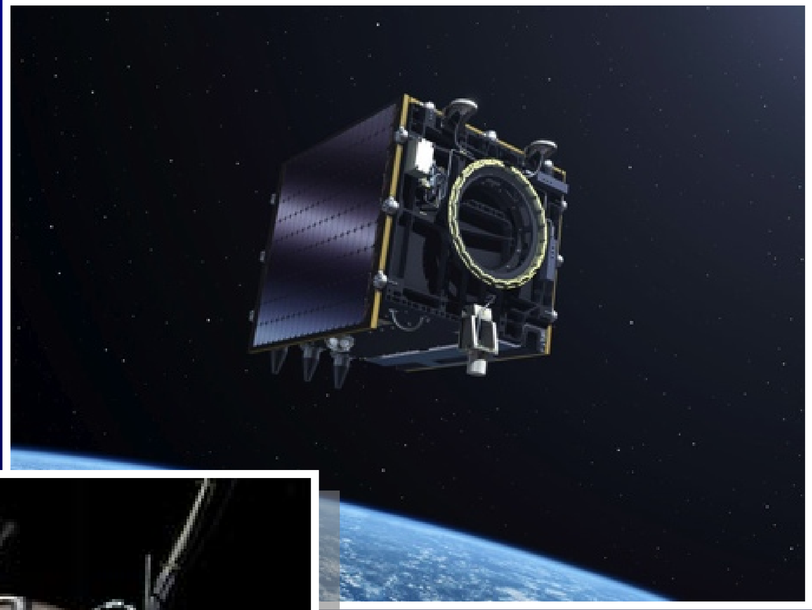


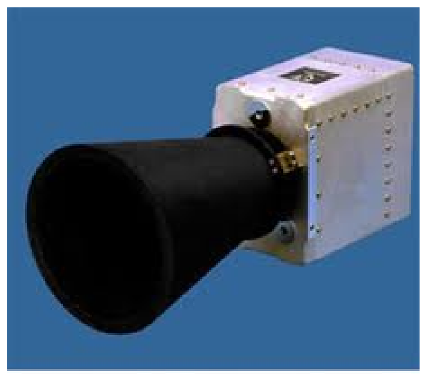
Northrop Mini-OWLS



Automated Celestial –– Current Space Applications

Commercial star trackers





A star tracker module, similar to those on the GP-B spacecraft.

Used for attitude sensors for satellites

Automated Celestial Technology

- Old
  - Gimbaled
  - Photomultipliers, vidicons, or similar detectors
  - Single-star observations
  - Programmed sequence of observations
- New
  - Strapdown (no moving parts)
  - CCD, CMOS, or near-IR detectors
  - Multiple stars observed in each field
  - No active pointing, automatic star recognition

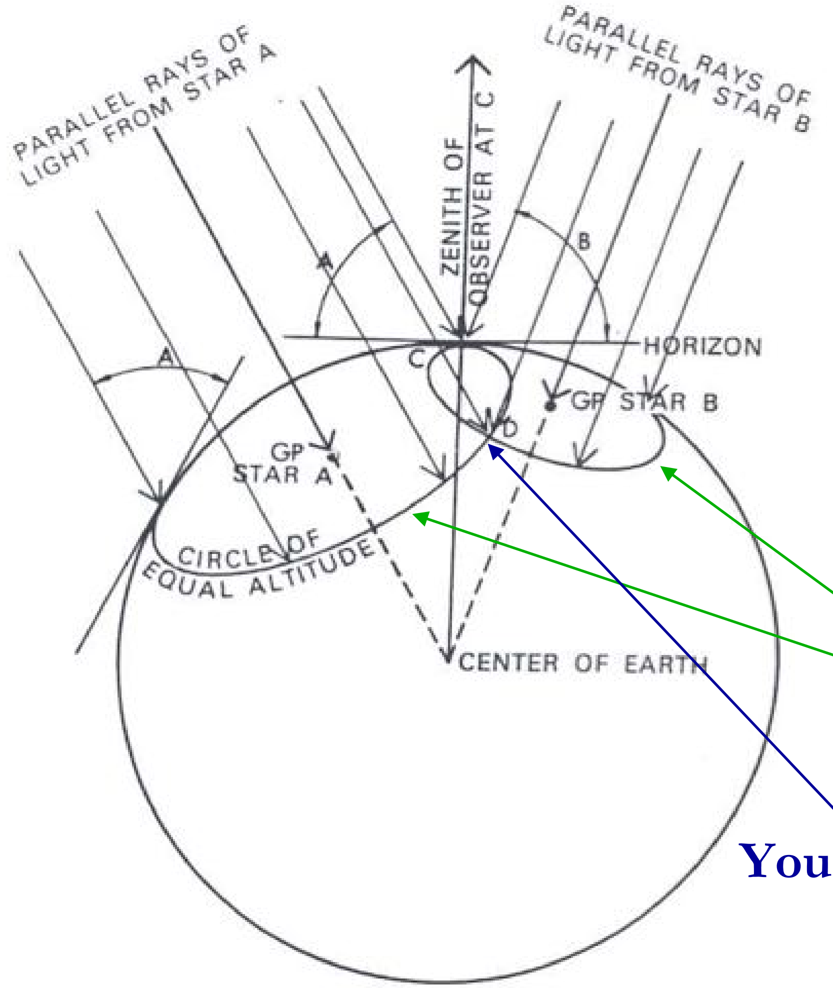
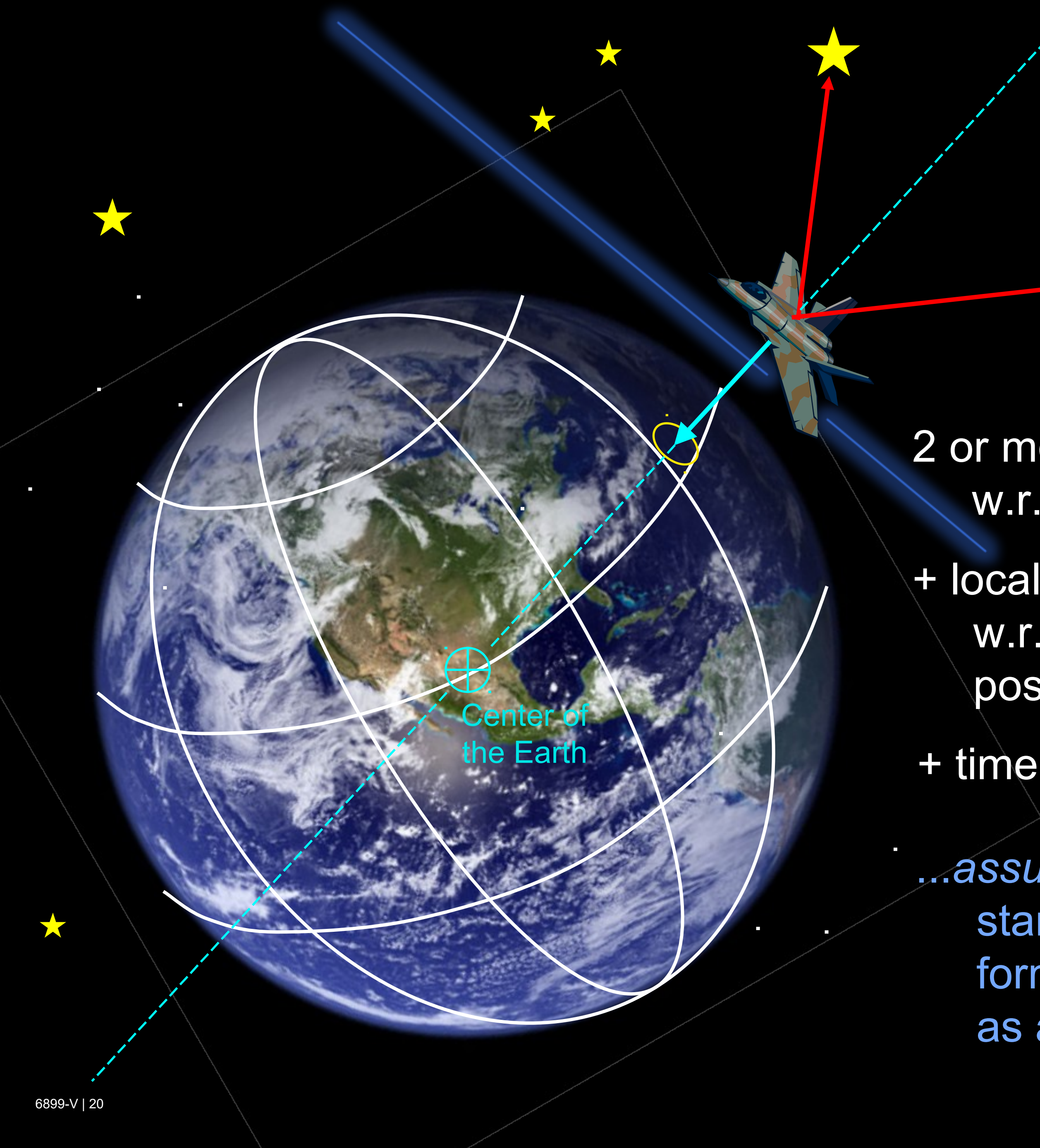


Figure 1907c. Circles of equal altitude for two stars. A—Altitude of star A from position of observer on circle of equal altitude. B—Altitude of star B from position of observer on circle of equal altitude. C and D—Two intersections of circles of equal altitude.

Circles of position

You must be at either point C or D



2 or more stars ⇒ 3-axis attitude
w.r.t. stars (inertial system)

\+ local vertical ⇒ attitude
w.r.t. horizon *and*
position along a line in space

\+ time ⇒ latitude and longitude

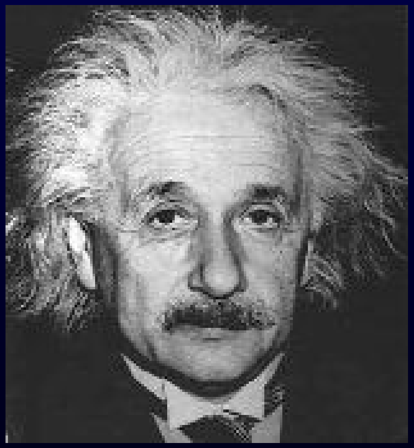
...assuming
star catalog data and
formulas for Earth orientation
as a function of time

A Technical Challenge: Determination of the Vertical

- An essential part of celestial navigation based on stars
- Precision tiltmeters (inclinometers) are a solution for fixed positions on land
- However, moving observers — the most important case — present a more fundamental problem

:

Vehicle accelerations cannot be distinguished from gravity using an internal ("lab") measurement



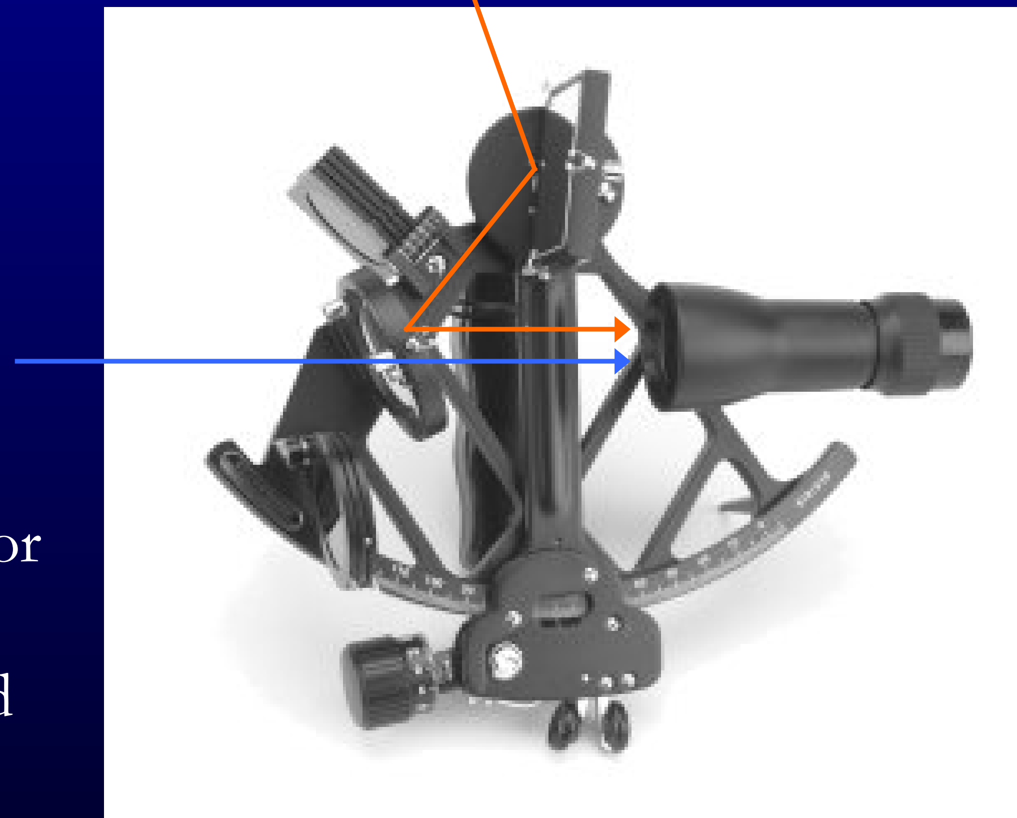
Determination of the Vertical

Solutions:

1. Use external natural surrogates for the vertical
   - Horizon
   - Atmospheric refraction of star positions
   - Local average sea surface
2. Use vertical direction computed by INS
   - Better: Use stellar observations to correct the INS orientation
3. Don't use stars! Observe nearby celestial objects –– artificial Earth satellites –– and use triangulation to determine location

Scheme 1

The Vertical as Defined by the Horizon



In the traditional scheme for open-ocean celestial navigation, the sextant field of view combines two sightlines, one to the star and the other to the horizon.

The Vertical as Defined by the Horizon

Atmospheric Refraction as an Issue:

- The line of sight to the horizon goes through a lot of air $\Rightarrow$ the horizon itself is refracted (typically by ~1/2 arcminute)
- We cannot assume that the refraction will be constant in all directions; the horizon is a somewhat warped circle
- Refraction of the sea horizon depends on the air-sea temperature difference; even a few degrees variation results in many arcseconds difference in the horizon's depression wrt the vertical
- The horizon is likely to be the first thing to become indistinct when weather conditions deteriorate

Scheme 2

Using Star Observations to Correct the INS Orientation

- Inertial Navigations Systems (INS) are a form of computerized dead reckoning, using data from acceleration and orientation sensors (accelerometers and gyros)

- INS *computationally* track position, velocity, orientation, and spin (navigation state) in a single mathematical solution (Kalman filter)

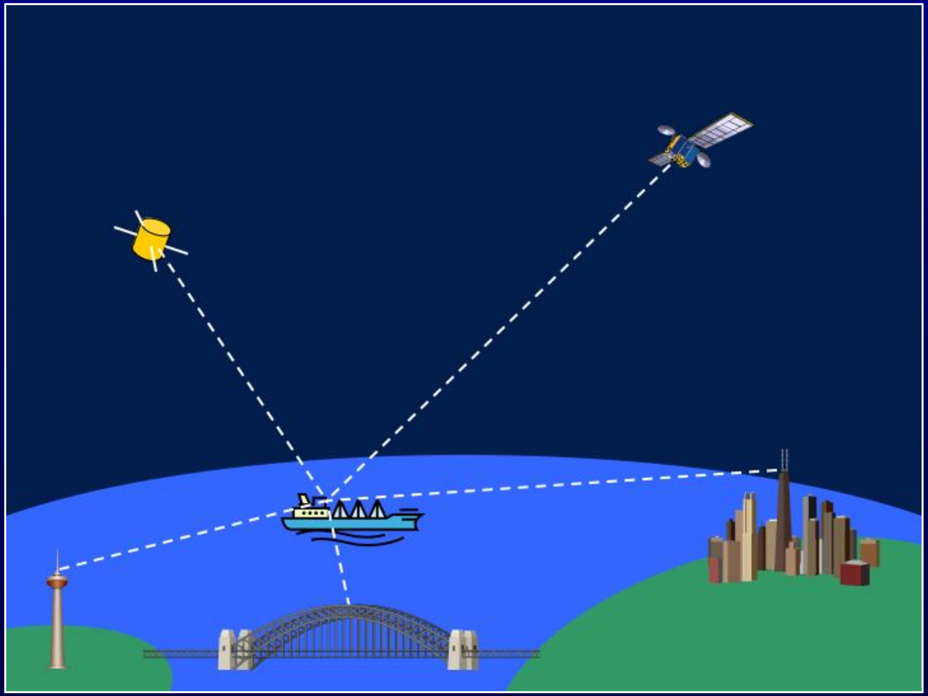
- All INS navigation solutions are subject to various errors, including drift

- Stellar observations can be used to correct the computed orientation – thus improving the *entire* solution

Scheme 3

Eliminating the Vertical

- The problem with celestial navigation is that the stars are (essentially) infinitely distant — the angles between them don't change as we move around
- If we could instead observe relatively nearby objects, we could apply **3-D triangulation** and we would not need to determine the local vertical



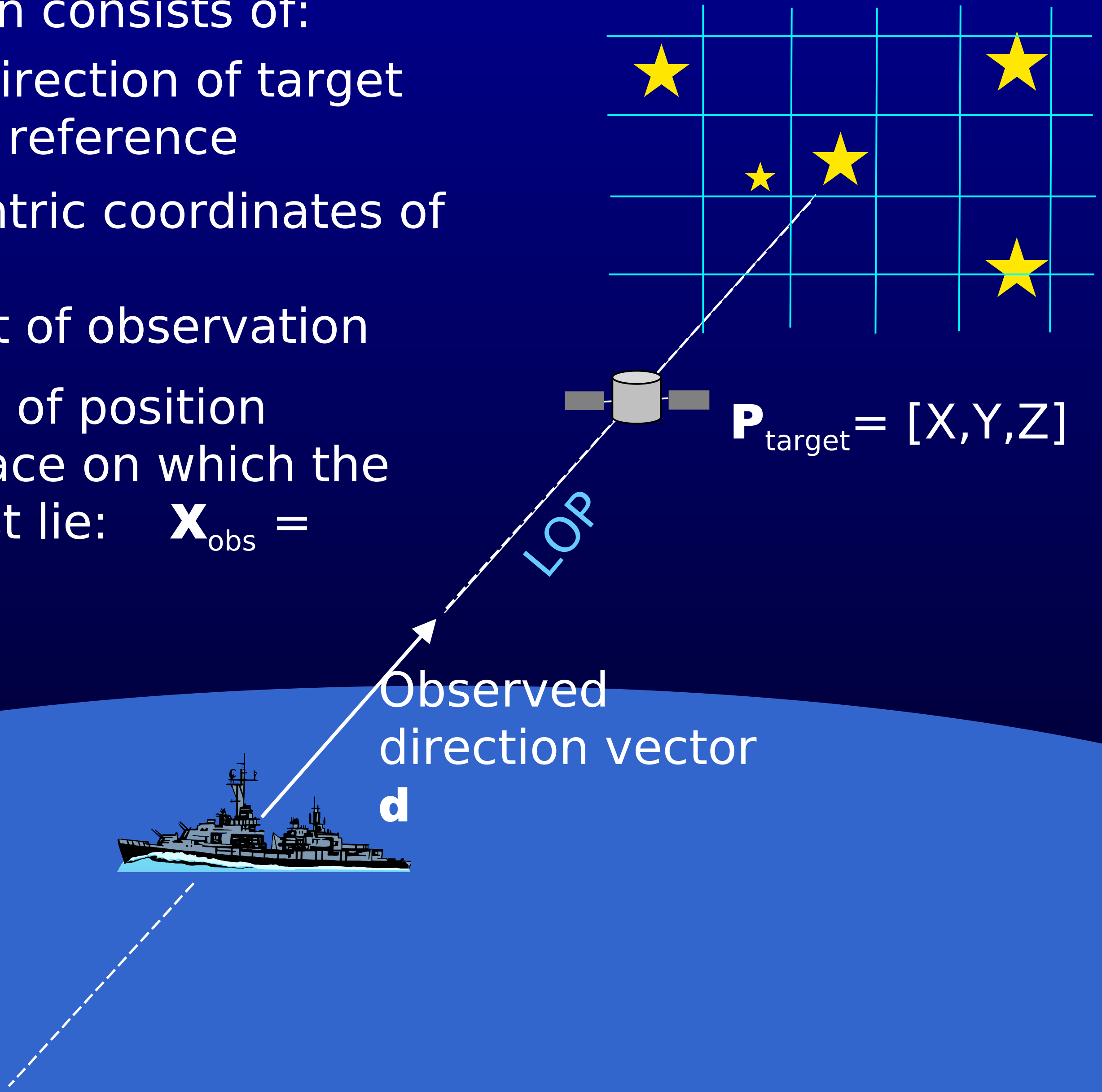
- The "nearby objects" could be artificial Earth satellites observed against a star background

Observation Geometry

An observation consists of:

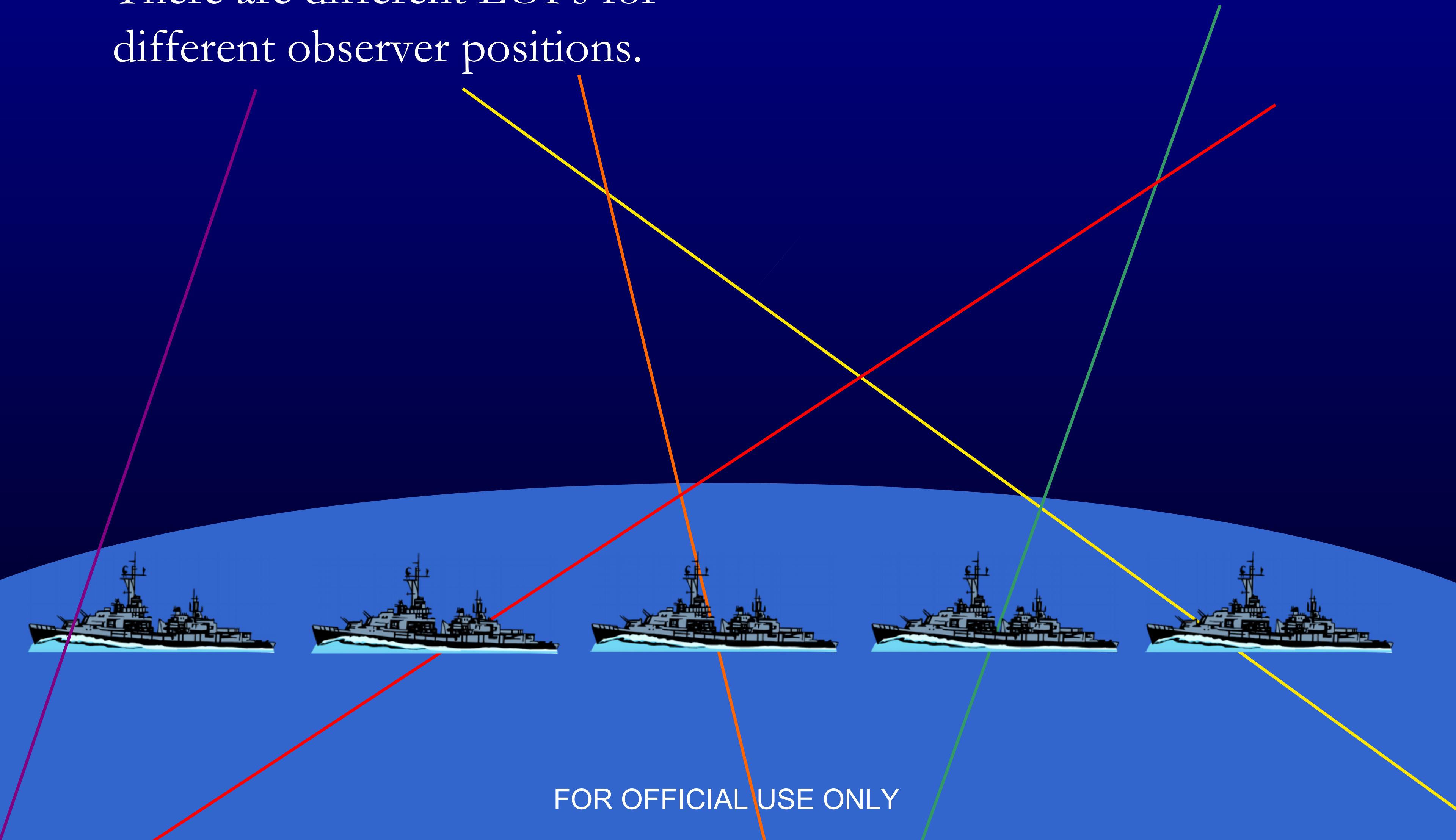
- Observed direction of target wrt stellar reference system
- 3-D geocentric coordinates of target at instant of observation

Defines a line of position (LOP) in 3-space on which the observer must lie: $\mathbf{X}_{obs} = \mathbf{P}_{target} + r\,\mathbf{d}$



Moving Observer Solution

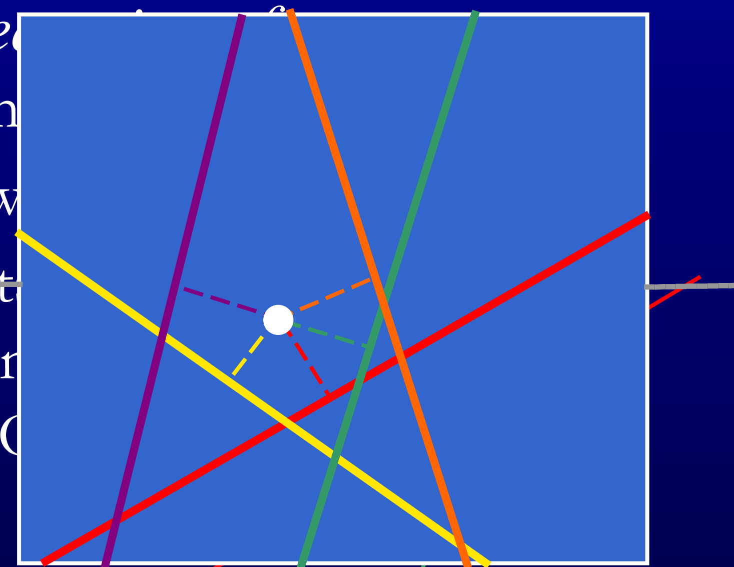
There are different LOPs for different observer positions.

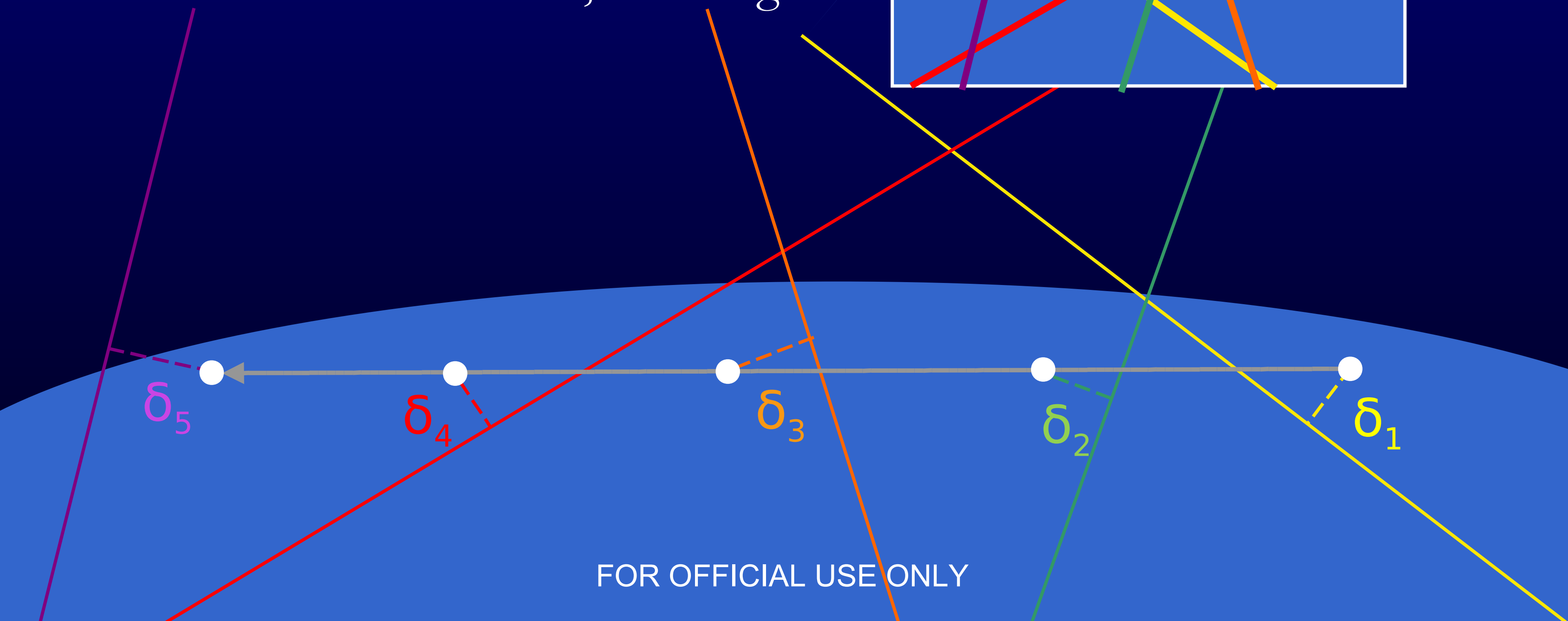


Moving Observer Solution

For this case, the algorithm finds the *e*[...] *motion* $\mathbf{X}(t) = \mathbf{X}_0 + \mathbf{V}t + \mathbf{C}(t)$ that m[...] sum of the δ_i^2. Each δ_i is associated w[...] *separate point* in space that represent[...] modeled position of the observer wher[...] observation *i* was made, resulting in LO[...]

This is equivalent to a set of LOP's converging on a single point as seen from a moving reference frame.





Recent & Current Activity

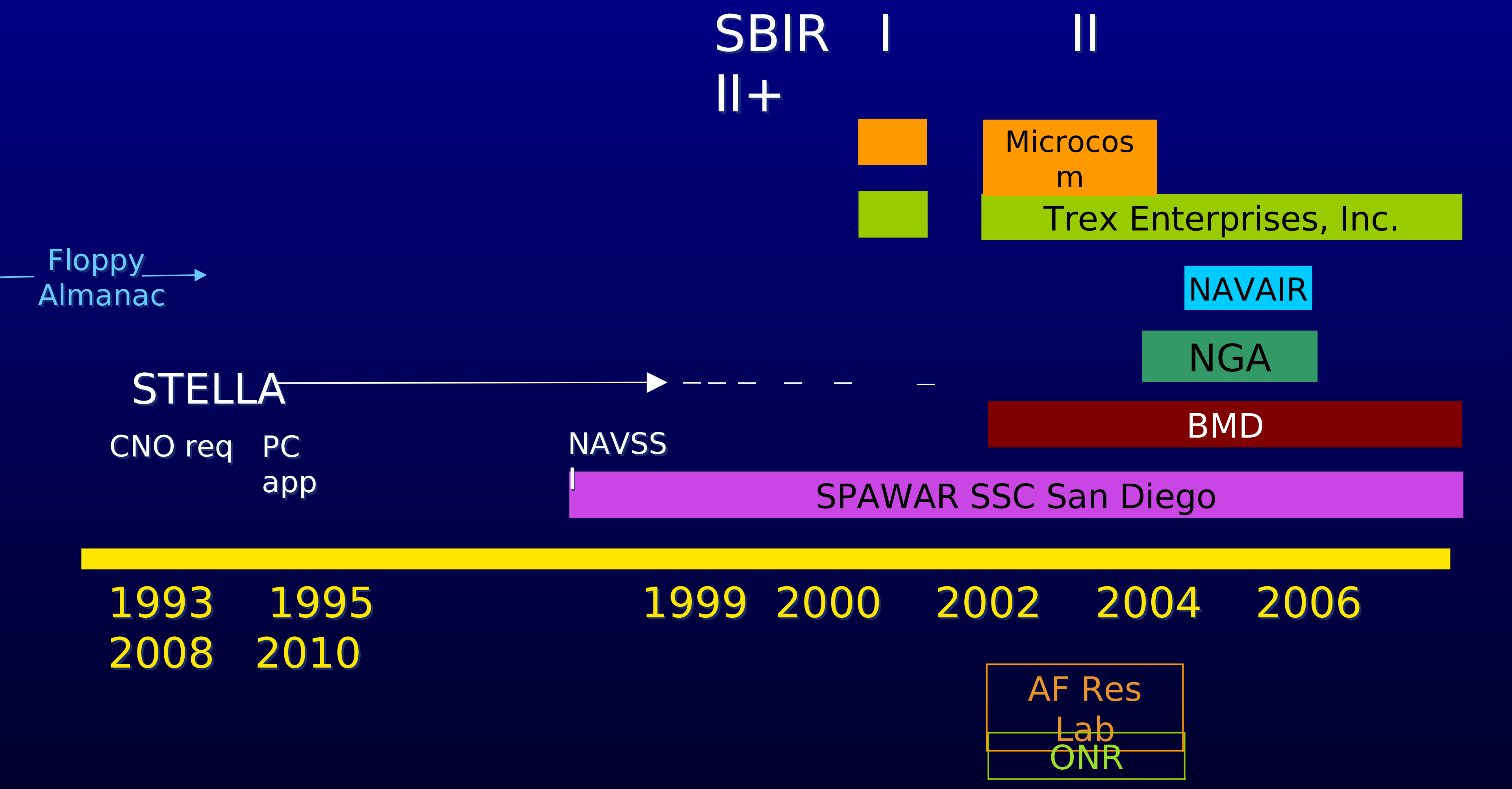
- Trex Enterprises Corporation, San Diego
  - Focus on <100 m accuracy, day + night operation at sea level
  - Funded by ONR, SPAWAR, AF Research Lab, NGA, NAVAIR, BMD
  - Resulted in a prototype instrument for fixed locations on land, which resulted in an automated zenith telescope for NGA surveying
- Draper Lab, Massachusetts
  - Shipboard tests showed feasibility of using LEO satellites as optical targets
  - Developing specialized all-sky camera for this
  - May be used as an input sensor to the Navy's GPNTS navigation system
- DoD Star Tracker Working Group has been working to define a coherent strategy for future R&D in this area
  - POC: Dr. Bryan Dorland, USNO
  - Testbed instruments at USNO; space experiments planned

Conclusions

- GPS vulnerabilities can be overcome by diversifying the sources of navigation information
- Celestial navigation is still an important component of the modern navigation picture
- Automated celestial observing systems have been reliably used for a half-century in critical national defense systems
- Modern sensor systems provide a new opportunity for developing compact and accurate automated celestial observing systems
- Observing Earth satellites against a star background — for a triangulated navigation fix without the need for a vertical determination — is an area of active R&D

End

USNO Work in Automated Celestial Nav



Satellites as Optical Targets — Which Ones?

Low Earth Orbits

Advantages:

- Bright
- Numerous
- Close, therefore higher positional accuracy

Disadvantages:

- Very high angular rates
- Generally poor orbital accuracy
  - Except for some geodetic sats
- In shadow much of the time

Medium and Geosync Earth Orbits

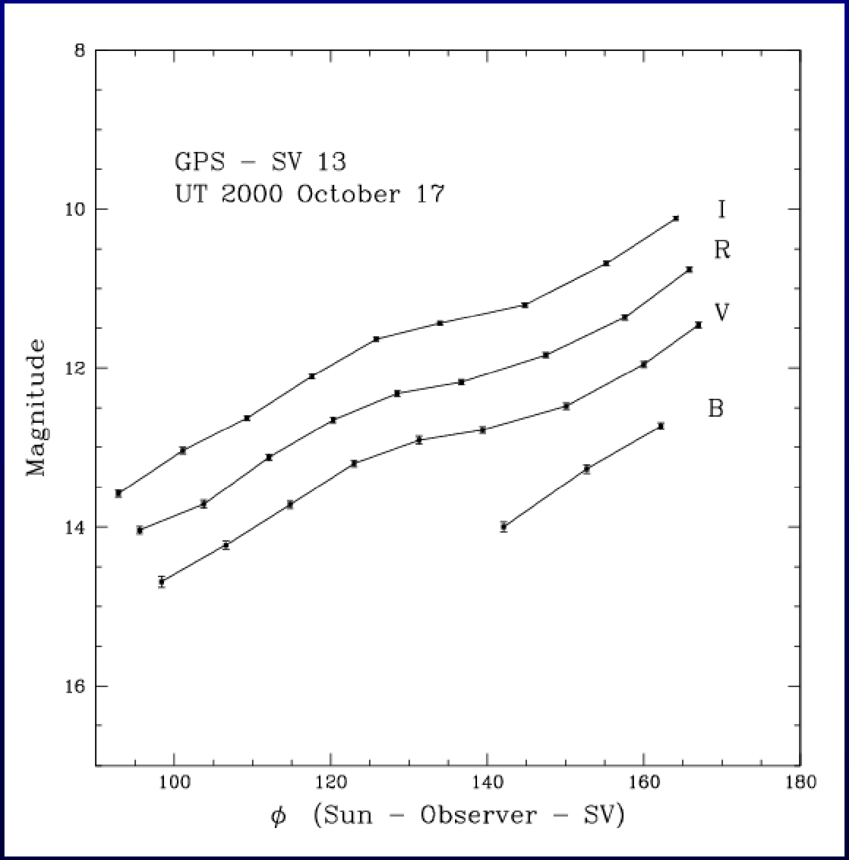
Advantages:

- Many have precise orbits
- In sunlight most of the time
- Lower angular rates
- GNSS sats have good nav geometry

Disadvantages:

- Distant, therefore lower positional accuracy
- Faint

GPS Satellites as Optical Targets



from Vrba (2005) PPT

Well established photometric properties: USNO/FS – Aerospace Corp. study by Fliegel, Warner, & Vrba (2001) and Vrba follow-ons to 2005

1.3-meter Telescope at USNO Flagstaff

2x3 CCD array in focal plane, chips individually programmable

Photos by Marc Murison

Lessons Learned (I)

- Pay attention to nature
  - Sophisticated instrumentation can't overcome fundamental limitations imposed by the underlying natural phenomena
- Determining the vertical is a hard problem
- The "average sky" is not typical — star counts per unit area of sky are highly variable
- For strapdown (target of opportunity) systems, 70% of the stars observed will be in the faintest magnitude unit that can be detected

Continued…

Lessons Learned (II)

- The near IR has a lot of advantages
  - Darker sky, more stars
- "High altitudes" are not space!
  - 60,000 ft: still below 10% of the atmosphere
  - 80,000 ft: still below 5% of the atmosphere
- One size does not fit all
  - Vastly different instrumentation issues for shipboard/sea-level applications than for aircraft systems
  - Even within each category, the trade space is large
    - Aperture, focal length, field-of-view, band, type of sensor, pixel size, …

End