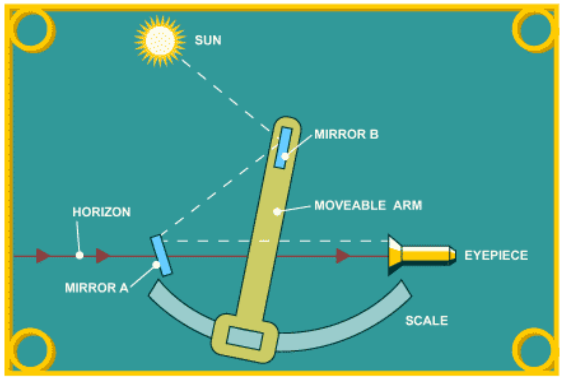
Maritime Navigation

Jim Doherty
15 April 2010
Trieste, Italy



Graphic: www.pbs.org

Objective

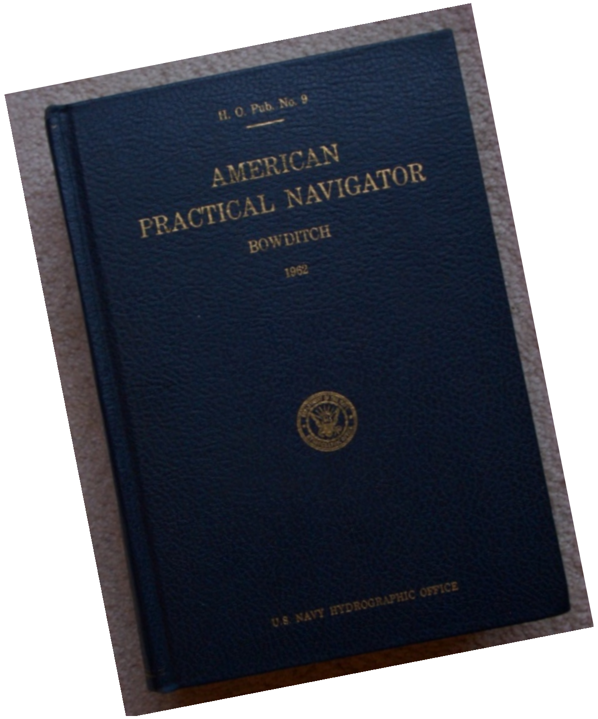
- To learn the long tradition & some unique aspects of maritime navigation
  - *Emphasis on electronic navigation systems used by mariners*
  - *Brief history of these systems*
  - *And consideration for future*

Outline

- Background
- Requirements & Standards
- Electronic Navigation History
- Break
- Current Radionavigation systems
  - *eLoran, DGPS, e-Navigation*
- Conclusions

Classic Reference Texts

1. Bowditch, Nathaniel, American Practical Navigator, US Navy Hydrographic Office, 1962
2. Hill, J.C., Utegaard, T.F., & Riordan, G., Dutton's Navigation and Piloting, US Naval Institute, 1964



Interesting Reading

1. Sobel, Dava, Longitude, Walker Publishing Co., Inc., 1995
2. Lansing, Alfred, Endurance: Shackleton's Incredible Voyage, Carroll &Graf Publishers, 1999
3. Thomsen, Niels P., Men of the Menkar: USCG World War Two Naval Exploits (Books 2 &3), Von Buchold Press, 1999
4. Lundy, Derek, The Way of a Ship, Beara, Inc., 2002
5. Kinder, Gary, Ship of Gold in the Deep Blue Sea, Atlantic Monthly Press, 1998
6. Brogdon, Bill, Boat Navigation for the Rest of Us: Finding Your Way By Eye and Electronics, McGraw-Hill, 1995

Background

- Navigation
  - *"Navigation is the process of directing the movements of a craft from one point to another. To do this safely is an* art. *…man has transformed that art into a* science*…"*

    (Bowditch, p15)
  - *"Navigation is defined, formally, as the art or science of conducting a ship or aircraft from one position to another."*

    (Dutton's, p1)

Art & Science

- According to Dutton's (p1)
  - *"Science is involved in the computation of navigational solutions and in the development of methods, instruments, devices, tables, and almanacs."*
  - *"The application of these aids and the interpretation of information received … constitute an art requiring skill, experience and judgment."*

Navigation Means

- Dutton's defines four navigation divisions
  - *Dead reckoning (DR)*
  - *Piloting*
  - *Electronic navigation*
  - *Celestial navigation*

Dead Reckoning

- Approximate position
  - *Deduced from last known position*
  - *Based on direction & estimated speed*
- Originally “deduced reckoning”
  - *Shortened to “ded. reckoning”*
  - *And in English “ded.” became “dead”*
- Often abbreviated “DR”

Classic Navigation

- Piloting – navigation based on
  - *Landmarks, charted aids, soundings*
  - *Used in close proximity to shore or harbor*
- Celestial navigation – based on
  - *Celestial objects – sun, stars, planets, moon*
  - *Used at sea – beyond line-of-sight to shore*

Electronic Navigation

- In 1960s (Dutton's et al)
  - *Considered an extension of piloting*
  - *Using radio signals from charted terrestrial locations*
- Today with GPS/GNSS
  - *Satellites as new "celestial" objects*
  - *Extension of celestial using electronic systems*

All Available Means – 1960s

USCGC Madrona

Navigator – LT(jg) Doherty

- Navigation by
  - *Visual piloting*
  - *Radar*
  - *Radiobeacons*
  - *Loran-A*
  - *Celestial*
  - *Bottom contour & soundings*
  - *Dead reckoning*

Photo: Historic American Engineering Record, National Park Service, 2003, p27

Electronic Navigation

- 1960s
  - *Radiobeacons*
  - *Radar*
  - *Loran-A*
- 1970s
  - *Loran-C*
  - *Omega*
  - *Loran-A*
- 1990s
  - *GPS*
  - *DGPS*
  - *Radiobeacons*
  - *Omega*
- Today
  - *eLoran*
  - *Loran-C*

All Available Means – today

- Coastal & restricted waters (piloting)
  - *Visual – landmarks, aids – soundings*
  - *Electronic – radar, GPS, DGPS, eLoran*
  - *Dead reckoning*
- At sea – beyond line-of-sight navigation
  - *Celestial (sun, stars, planets, moon)*
  - *Electronic – GPS, eLoran*
  - *Dead reckoning*

Requirements & Standards

- Recommended information sources
  - *US Coast Guard Navigation Center*
    - www.navcen.uscg.gov
  - *International Maritime Organization (IMO)*
    - www.imo.org
  - *Radio Technical Commission for Maritime Services (RTCM)*
    - www.rtcm.org
  - *International Association of Lighthouse Authorities (IALA)*
    - www.iala-aism.org

Accuracy Goals – 1960-70s

- At sea – best possible
  - *~ 1-2 nautical miles*
- Coastal – 200 mile Exclusive Economic Zone (EEZ) limit
  - *¼ nautical mile*
- Harbor entrance & approach – within 20 miles
  - *100 meters, improving to 10-20 meters*

Accuracy Needed Today

- Appendix to IMO Resolution A.953(23) of 5 December 2003
  - *Requirements for radionavigation systems*
  - *Includes accuracy requirements for*
    - Harbor entrance, approach, & coastal waters – 10 meters
    - Ocean waters

      –100 meters

IMO Requirements

- Categories
  - *Harbor entrance, approach, & coastal – high traffic volume or significant risk (HEA-H)*
  - *Harbor entrance, approach, & coastal – low traffic volume or lower risk (HEA-L)*
  - *Ocean areas (OCEAN)*
- Details next chart

Source: Appendix to IMO Resolution A.953(23) of 5 December 2003

IMO Requirements (cont.)

- Accuracy @ 95% probability
  - *10 meters for HEA-H/HEA-L*
  - *100 meters for OCEAN*
- Update rate for HEA-H, HEA-L, & OCEAN
  - *10 seconds for displays*
  - *2 seconds for automated systems*
- Availability & Reliability
  - *HEA-H: 99.8% over 2 years; & 99.97% over 3 hours*
  - *HEA-L: 99.5% over 2 years; & 99.85% over 3 hours*
  - *OCEAN: 99.8% over 30 days; & no spec on reliability*
- Non-availability warning
  - *10 seconds for HEA-H & HEA-L*
  - *As soon as practical for OCEAN*

US Revenue Cutter Bear

Picture from www.uscg.mil

Aboard USRC Bear ~1895

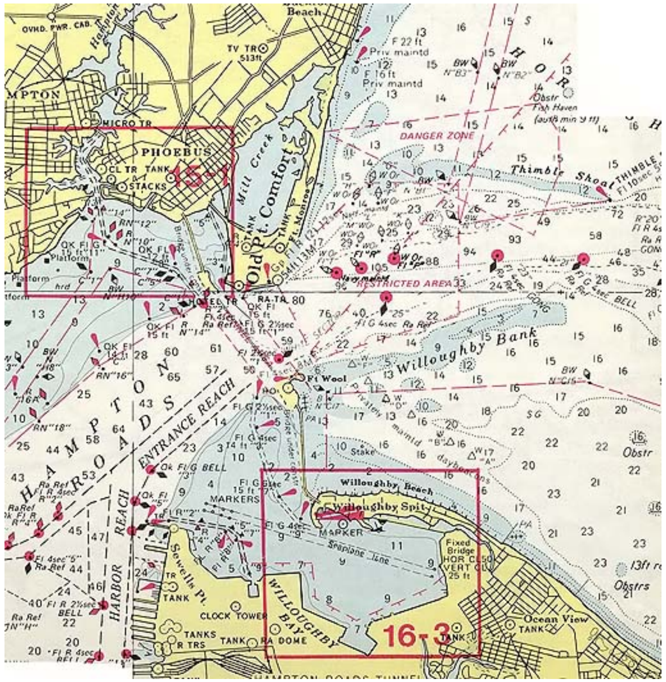
Navigator's toolkit

- Navigation charts
- Chart instruments
  - *Parallel rules*
  - *Dividers*
- Sextant
  - *Almanacs & tables*
- Compass
- Chronometer
- Speed log
- Angle measuring device

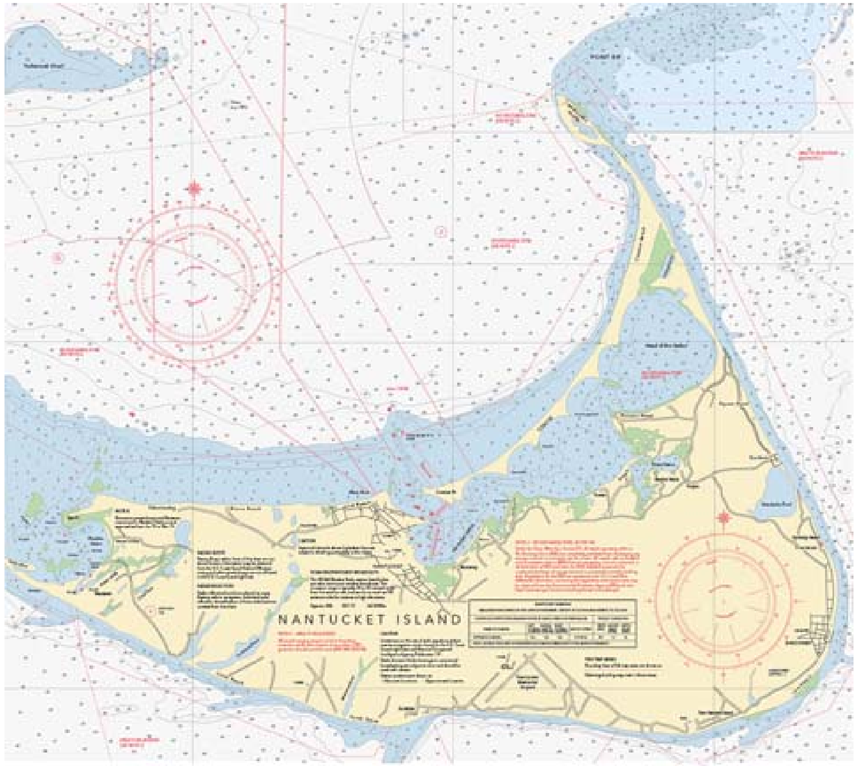
CAPT "Hell Roarin' Mike" Healy & pet parrot

Navigation Charts

Hampton Roads, Virginia: approach to Norfolk, Newport News, Portsmouth, et al



Nantucket, Massachusetts

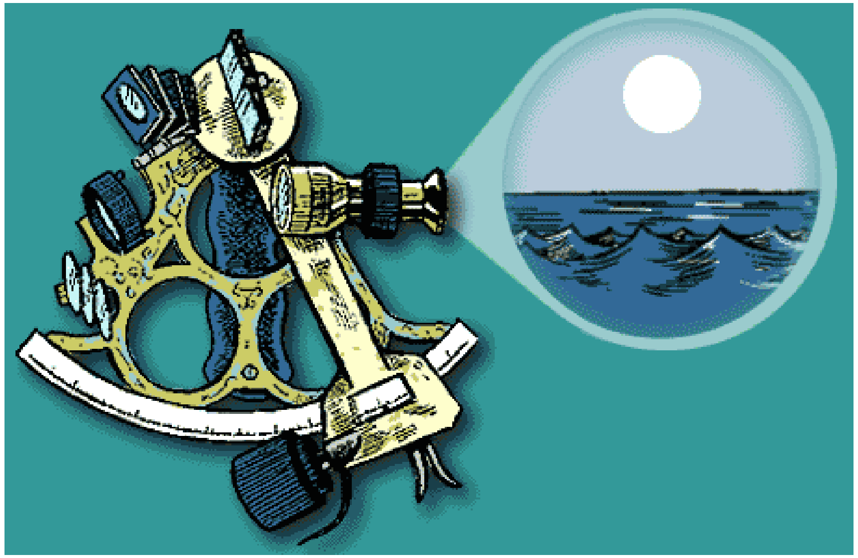


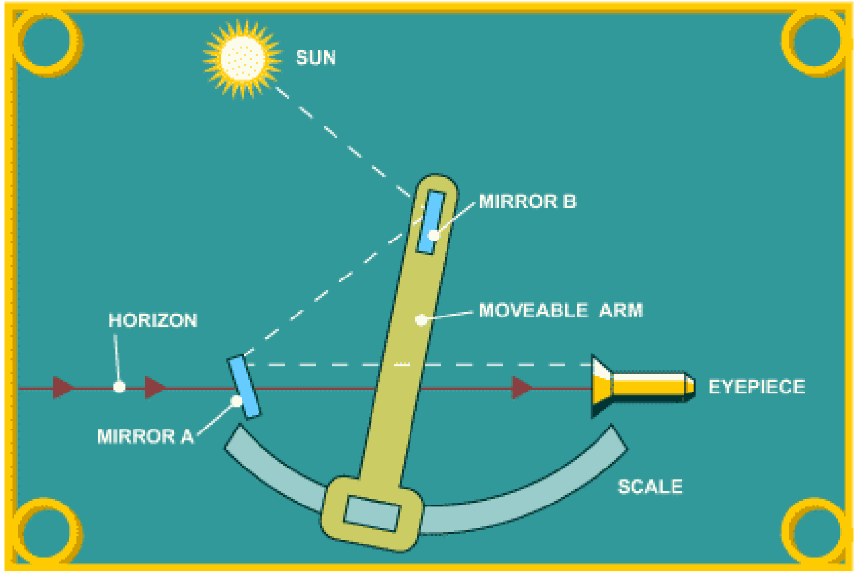
www.roadstothefuture.com

www.weebsite.ca

Maritime Sextant

Measures angles in degrees, minutes & tenths (~10 seconds) of arc accuracy





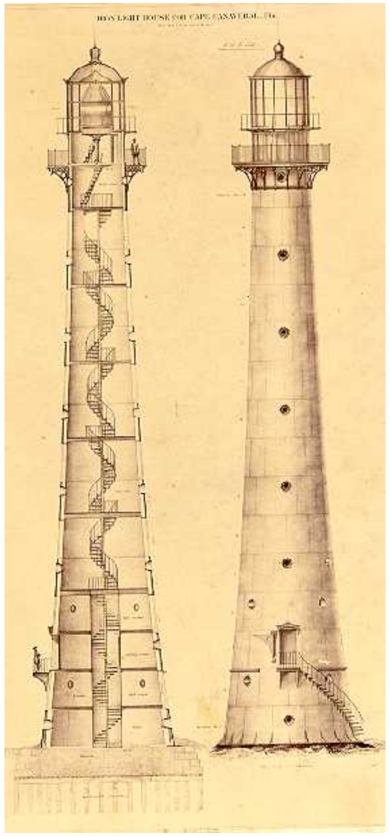
Source: www.pbs.org

Maritime Sextant

Source: www.stanleylondon.com

Classic Navigation Tools

Cape Canaveral lighthouse plans



www.uscg.mil

Alidade

en.wikipedia.org

Binnacle & magnetic compass

www.antequesofthesea.com

Celestial Navigator's Day

- 0400-0800
  - *Navigator's watch*
  - *Morning stars & position fix*
- 0800-1200 & 1200-1600
  - *Morning sun line & estimated position*
  - *Local apparent noon & running fix*
  - *Wind chronometers*
  - *Afternoon sun line & running fix*
- 1600-2000
  - *Evening stars & position fix*
  - *Plan next day's course & navigation*
- Backup plan – DR

“Shooting” Stars

- Prepare (navigator & assistant)
  - *Select stars based on location & almanac*
  - *Synchronize watch with chronometer*
- Identify & shoot each star or planet
  - *Note time & angle*
- Calculate & plot lines of position
  - *Table look-up, interpolate, etc.*
  - *Compare “fix” with DR-estimated position*

Electronic Navigation

- Navigation by
  - *Visual piloting*
  - *Radar*
  - *Radiobeacons*
  - *Loran-A*
  - *Celestial*
  - *Bottom contour & soundings*
  - *Dead reckoning*

Photo: Historic American Engineering Record, National Park Service, 2003, p27

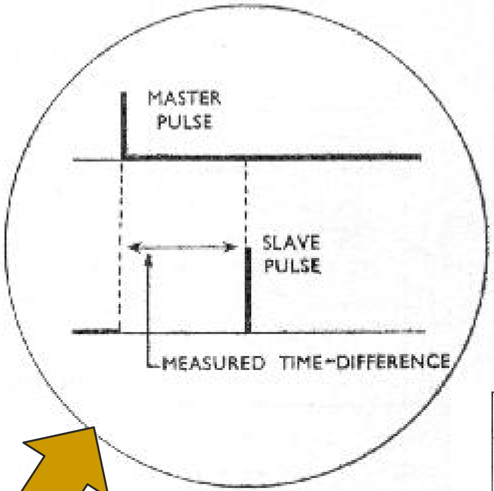
Loran-A

- World War II development
  - *Goal: accuracy of 1000 feet @ 200 miles*
  - *1750-1950 kHz band, pulsed system*
- Master-secondary paired transmitters
  - *Two pairs (at least 3 transmitters) for fix*
  - *Difference in time (TD) received between master & secondary pulse in each pair for line of position (LOP)*

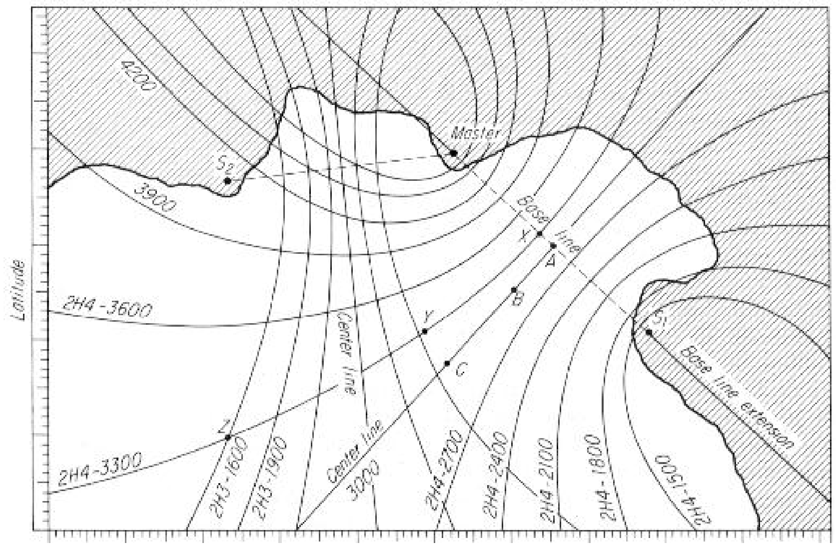
Reference: http://www.jproc.ca/hyperbolic/loran_a.html

Loran-A User Equipment

APN-4 Loran-A shipboard receiver



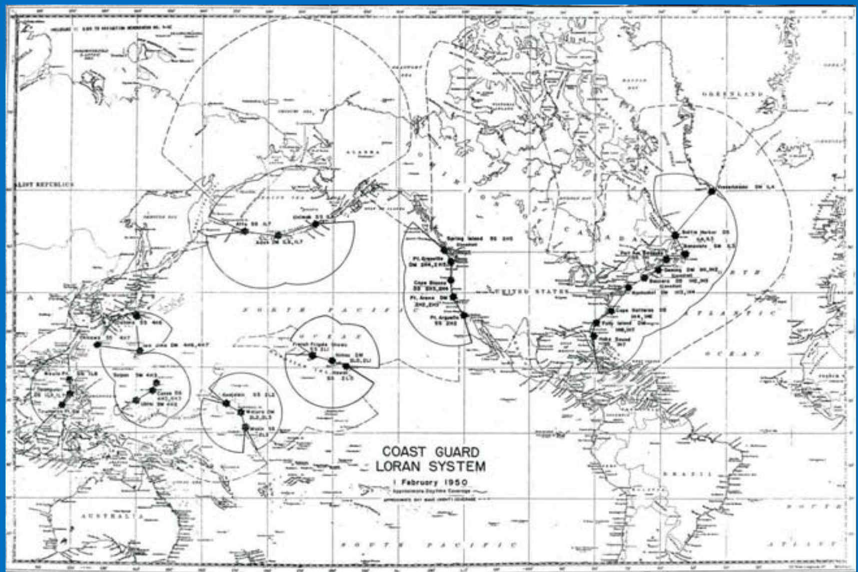
Plot indicated time difference (TD) on chart with preprinted Loran-A lines of position (LOP)

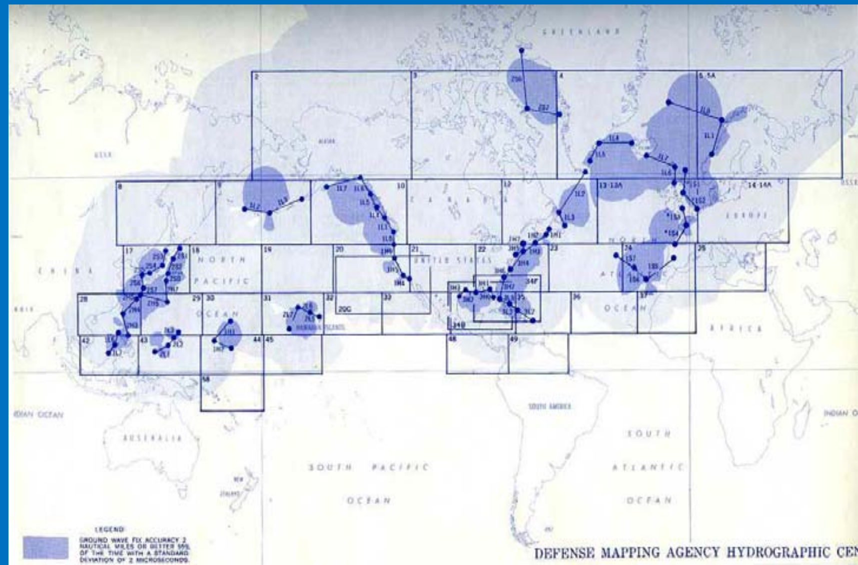


Reference: http://www.jproc.ca/hyperbolic/loran_a.html

Loran-A Coverage

Coverage 1950s **& 1970s**





Reference: http://www.jproc.ca/hyperbolic/loran_a.html

Loran-A Limitations

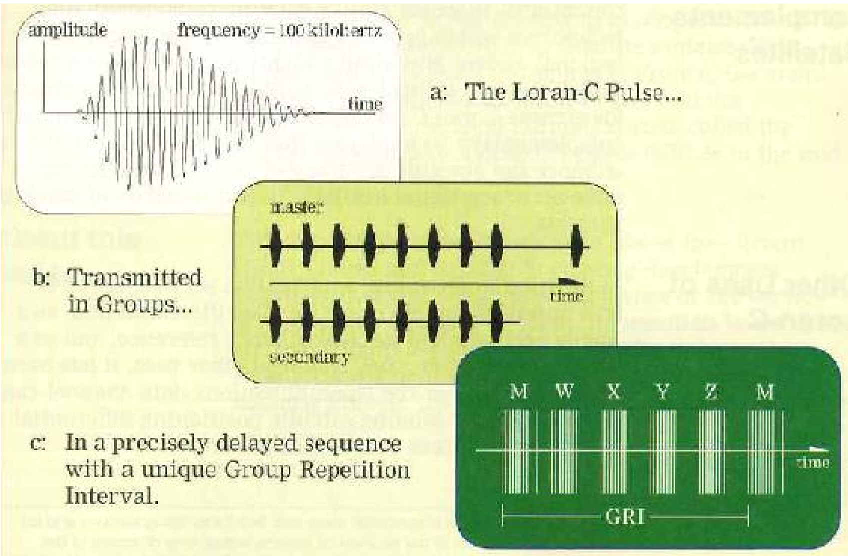
- Limited range
  - *Many transmitters needed*
  - *Propagation of ~2 MHz groundwave*
- Limited accuracy
  - *Best accuracy required groundwave reception; often hindered by skywaves*
  - *Propagation disturbances between master & secondary stations*

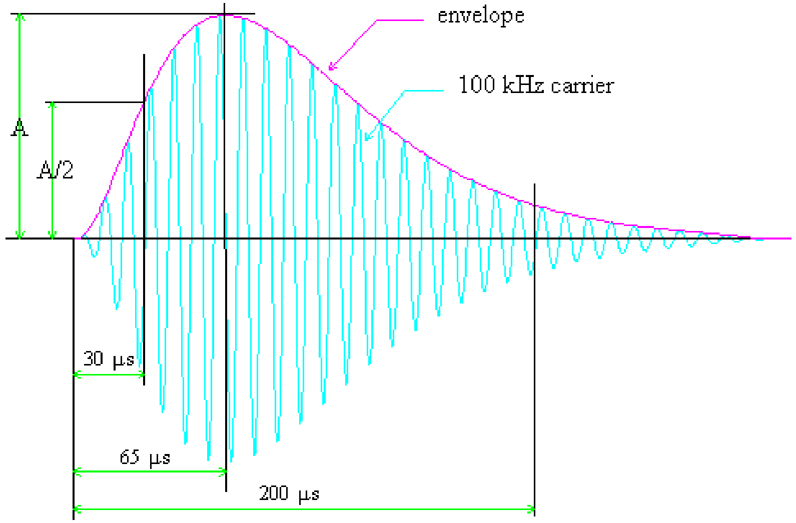
Enter Loran-C

- Same basic TD concept, better design
  - *Low frequency – 100 kHz*
    - Longer range groundwave propagation
    - More stable – enabled envelope (pulse leading edge) and carrier cycle matching for higher accuracy (coarse-fine) TD measurements
  - *Multiple pulses (8) – improved SNR*
    - Designed improve skywave rejection
- Master & multiple secondary "chains"

Loran-C Design Concepts

- Loran-C system design
  - Master & 2-5 secondary transmitters per chain
  - 8-pulse group from each
  - Designed to arrive in order throughout chain coverage



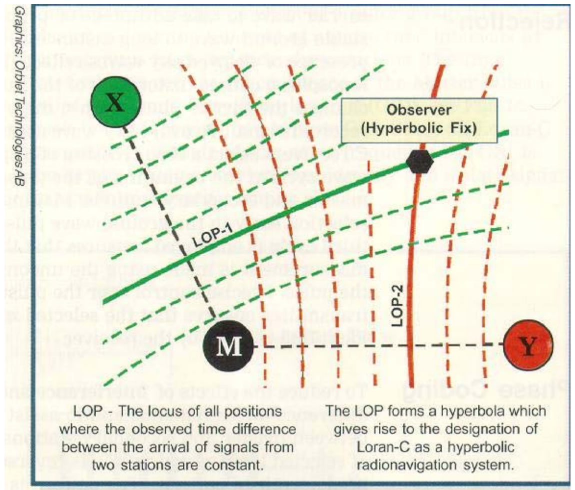


- Pulse design
  - Precise leading edge
  - Envelope match, then cycle match at 30 µs point (before earliest skywave arrival)

Reference: http://www.jproc.ca/hyperbolic/loran_c.html

Loran-C User Equipment

- Loran-C shipboard receivers (1970s-80s)
  - Decca 1024 (top)
  - TI 9000 (bottom)
- Plot TDs on preprinted Loran-C charts



Reference: http://www.jproc.ca/hyperbolic/loran_c.html

Loran-C Coverage

- **Coverage 1990s-2000s**
  - *Systems operated by host countries*
  - *Includes Russia's Chayka – Loran-C equivalent*
- **February 2010**
  - *USCG terminated Loran-C operations in US*
  - *Infrastructure remains for potential upgrade to eLoran*

Omega

- First global radionavigation system
  - *Sequentially timed pulses in VLF band*
    - 10.2 kHz, 11.33 kHz, 13.6 kHz, 11.03 kHz
  - *Global coverage from 8 transmitters operated by US (2) & 6 partner nations*
    - Norway, Liberia, Hawaii, North Dakota, LaReunion, Argentina, Australia, Japan
  - *Generally about 1-2 mile accuracy*
- Operations ended 30 September 1997

Now to Today … Break

USRC Bear

USCGC Bear

CAPT Healy

USCGC Healy

Source for USCGC Bear: www.fredsplace.org

Back to Today

USRC Bear

USCGC Bear

CAPT Healy

USCGC Healy

Source for USCGC Bear: www.fredsplace.org

Maritime Navigation

- Accuracy requirements (IMO)
  - *100 meters at sea*
  - *10 meters harbor entrance et al*
- Major electronic navigation aids
  - *GPS*
  - *Differential GPS (DGPS)*
  - *eLoran*
  - *e-Navigation*

Maritime DGPS Service

- Meets IMO requirements for harbor entrance, approach, coastal navigation
  - *10 meter accuracy, 10 second alarm time, availability, etc.*
    - Typically much better – 1-2 meters and 5 seconds to alarm
  - *Coverage to at least 20 miles from coast*
    - Generally dual coverage for all major ports & high volume coastal areas

DGPS – USCG's Beginning

Post-Exxon Valdez – 1989

USCG need to track ships throughout Prince William Sound

Used cooperative surveillance

- Ships report GPS data
- VTS applies corrections & displays on radar screen
- Local USCG buoytender requests same service
  - *Faster, more accurate way to position buoys*
- USCG plans DGPS buoy positioning system
  - *Upgrades to full navigation system concept*

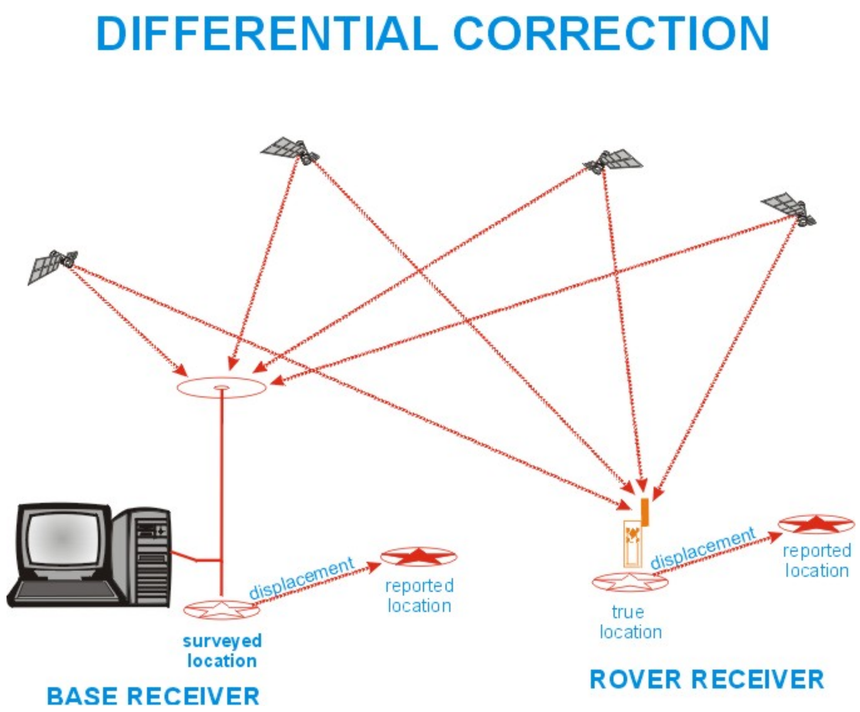
Photo: earthhopenetwork.net

How DGPS Works

Local Area System

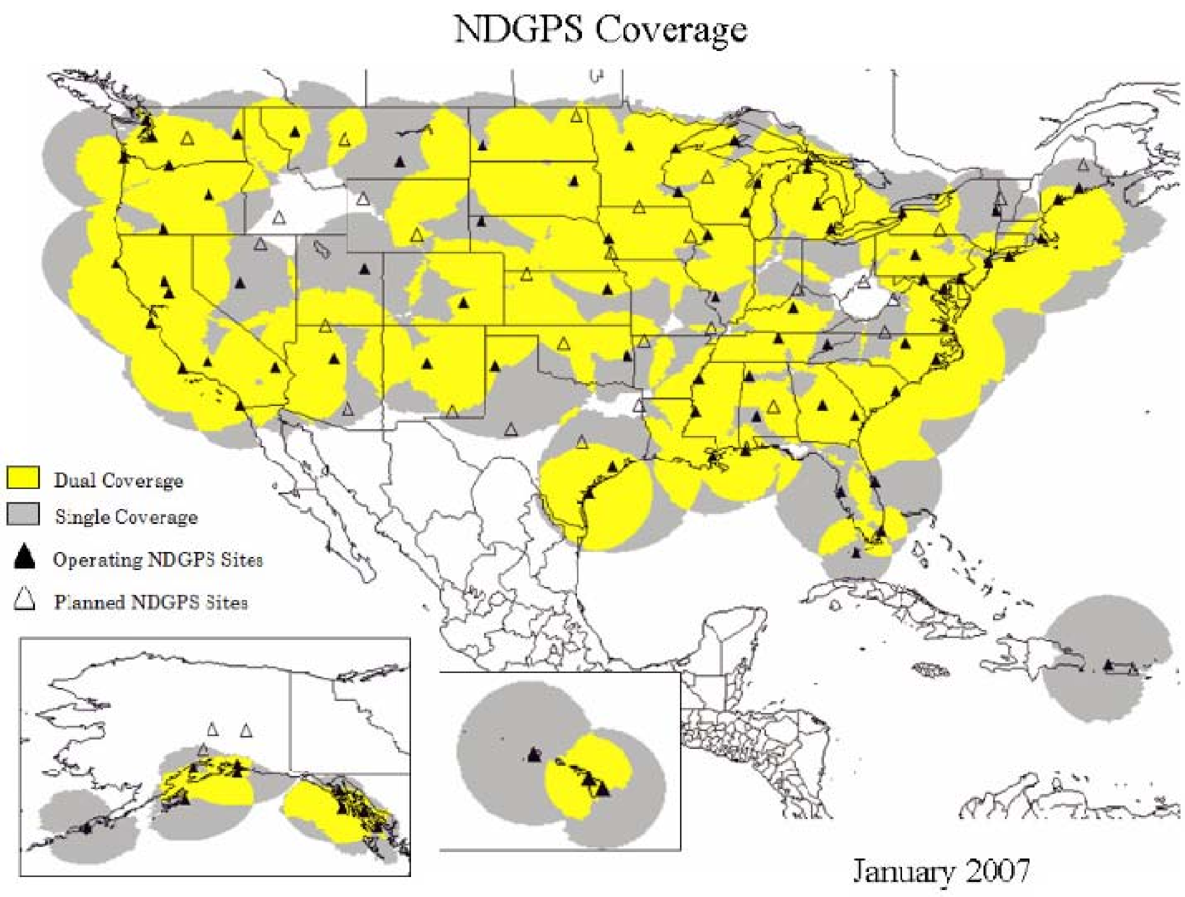
DGPS Signal Spec: US Coast Guard
COMDTINST M16577.1 April 1993

- Receive GPS at fixed reference stations
- Calculate correction for each SV used
- Broadcast corrections to users (rover receiver)
- Validate corrections using integrity monitor
- Record site performance data for legal purposes



Picture: www2.ocgi.okstate.edu

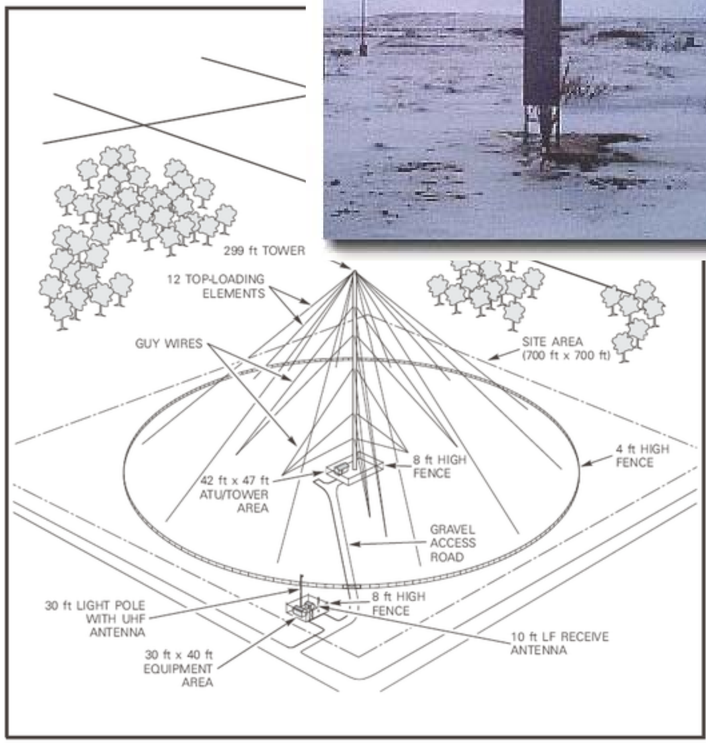
USCG DGPS Coverage



www.navcen.uscg.mil

Typical DGPS Sites

- **Modified radiobeacon site**
  - *80-100 foot top-loaded monopole radiobeacon broadcast antenna*
  - *Modified radiobeacon transmitter*
- **Modified GWEN site**
  - *300 foot TLM antenna*
  - *Modified GWEN transmitter*
- **Both**
  - *Two receiving antenna masts*
  - *Each with reference station & integrity monitor antennas*
  - *Two each reference station & integrity monitor receivers*



TYPICAL GWEN RELAY NODE

Photo: www.navcen.uscg.gov
Drawing: en.wikipedia.org

DGPS – Advantages & Not

- Advantages
  - *Improved accuracy & integrity*
  - *Under "sovereign control" in each port*
  - *Inexpensive (modify existing radiobeacon)*
  - *Common global standard (RTCM SC104)*
- Disadvantage
  - *Not independent system but augmentation*
    - If GPS reception is lost, there is no DGPS

eLoran

- True PNT service
  - *Maritime accuracy 10-20 meters*
  - *Time accuracy 50 ns & Stratum 1 frequency stability*
  - *Aviation integrity*
- True backup to GPS
  - *Independent of & compatible with GPS*
  - *Different propagation & failure modes*

eLoran Is NOT Loran-C

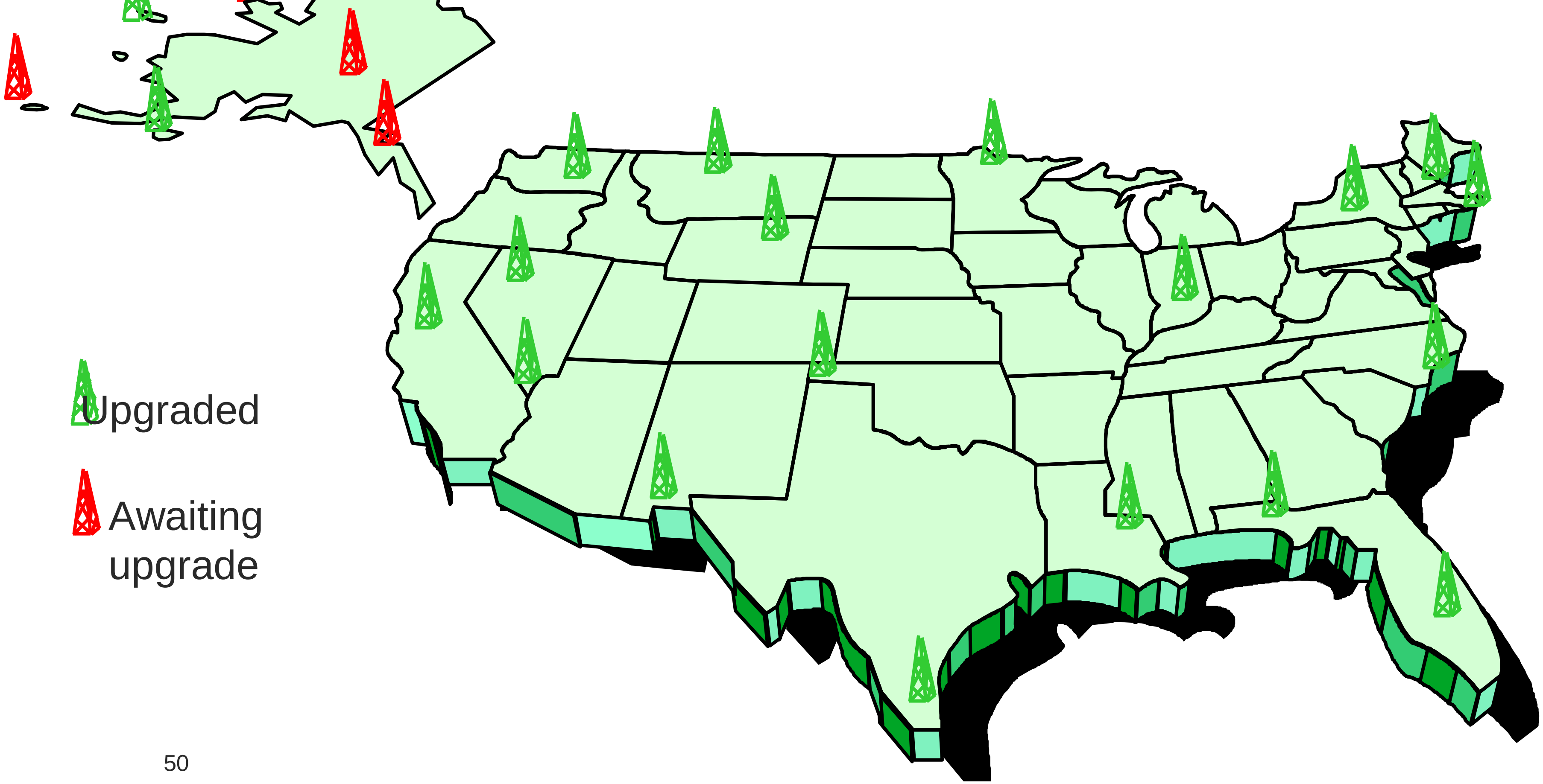
- Upgraded transmitter equipment
  - *All solid state, UPS, modern time system*
  - *Largest cost – upgrades completed in US*
- New operations concepts
  - *Time of transmission (TOT) control*
  - *Data channel for differential & integrity services*
- Modern user equipment
  - *Digital, all-in-view, seamless with GPS operations*
  - *Compact H-field antennas, integrated with GPS*

Data Channel Messages

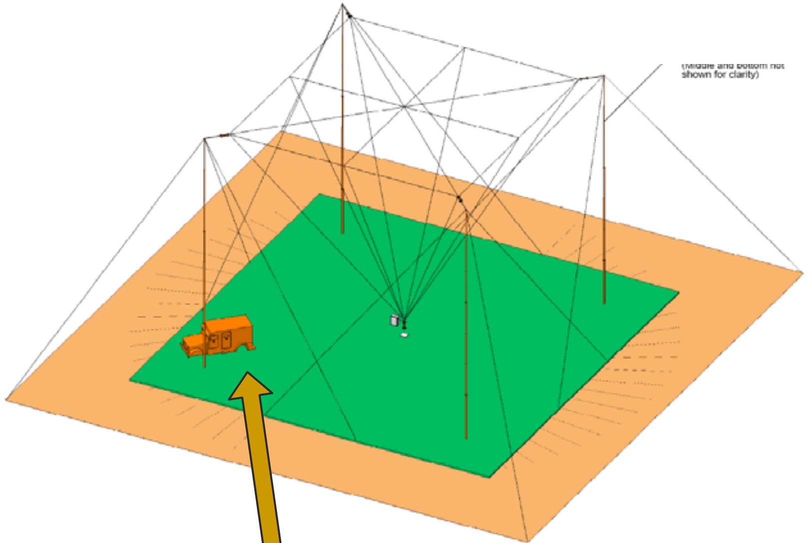
- Differential corrections
  - *Compensate for variation in signal propagation for improved accuracy*
- Integrity
  - *Validates that signals are safe to use*
- Other
  - *Time of day*
  - *Transmitter identifier*

eLoran in US *(fall 2009)*

- All18 operational sites in CONUS upgraded
- 2 of 6 operational sites in Alaska upgraded
- Equipment for 2 sites in Alaska purchased, awaiting installation



New eLoran Technology



eLoran Worldwide

- Existing Loran-C transmitters upgradable to eLoran
- RTCM Special Committee 127 (RTCM SC127) – Standards for Enhanced Loran (eLoran) Systems
- Southern hemisphere currently without eLoran infrastructure
- Opportunity to expand in
  - Africa
  - Australia
  - South America

e-Navigation

- Problem
  - *Larger & faster ships with smaller crews*
  - *Tighter schedules & crowded waterways*
- Solution – electronic navigation
  - *Electronic charts*
  - *Positioning system inputs*
  - *Display system*

Special thanks to Dr. Sally Basker & Dr. Nick Ward,
Trinity House, UK for photos & e-Navigation information

Today's Ships & Waterways

Need to Avoid

e-Navigation Definition

- IMO considers e-Navigation to be
  - *"...the harmonised collection, integration, exchange, presentation and analysis of maritime information onboard and ashore by electronic means to enhance berth to berth navigation and related services, for safety and security at sea and protection of the marine environment"*

Modern Ship's Bridge

- *Integrated electronics systems*
- *Tighter space & fewer crew*
- *Rely on systems, need*
  - *Standards*
  - *Reliable performance*
  - *Carefully designed redundancy*
  - *Seamless shift to backups*

How different is this from aircraft flight deck?

e-Navigation Tools

- Electronic hydrographic charts
  - *Provided by government authorities*
  - *Database of soundings, channels, buoys & other aids, obstructions & hazards, charted objects, etc.*
- Positioning systems
  - *At least 2, compatible & interoperable, but with dissimilar failure modes*

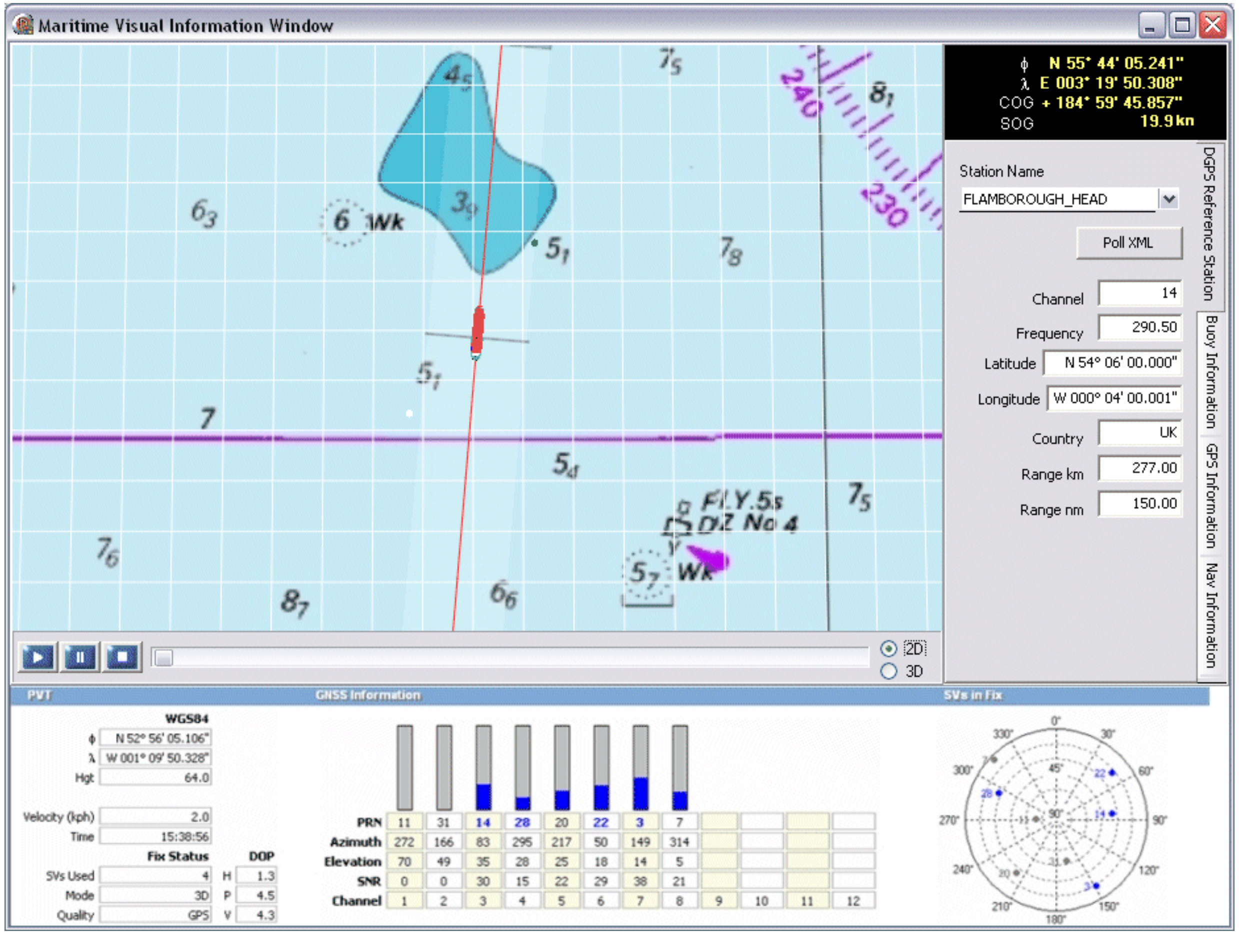
e-Navigation Tools (cont.)

- Electronic Charting & Display Systems (ECDIS)
  - *Uses chart database, positioning systems, other inputs to display own ship position, course, hazards, et al*
  - *Can be integrated with radar, automated information system (AIS), other sensors to display other vessels in area*

Electronic Chart Display

Typically includes

- *Own ship position, course, speed, track line, etc.*
- *Other vessels in area & their similar info*
- *Hazards, buoys, other charted objects*
- *Positioning system(s) & other systems in use*
- *Warnings*
- *Other info useful to interpret situation*



Positioning Systems

- Coastal & restricted waters (piloting)
  - *Visual – landmarks, aids – soundings*
  - *Electronic – radar, GPS, DGPS, eLoran*
  - *Dead reckoning*
- At sea – beyond line-of-sight navigation
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Conclusions

- Long history of maritime navigation
  - *Today, however, increasingly automated & reliant on electronic systems*
- Electronic positioning systems
  - *GPS &DGPS, plus eLoran, radar*
  - *Supplemented with visual & DR*
- e-Navigation concept
  - *Electronic charts & integrated display, etc.*

Information Sources

- Recommended information sources
  - *US Coast Guard Navigation Center*
    - www.navcen.uscg.gov
  - *International Maritime Organization (IMO)*
    - www.imo.org
  - *Radio Technical Commission for Maritime Services (RTCM)*
    - www.rtcm.org
  - *International Association of Lighthouse Authorities (IALA)*
    - www.iala-aism.org

Questions

Contact information

James T. Doherty

Institute for Defense Analyses (IDA)

4850 Mark Center Drive, Attn: STD

Alexandria, VA 22311

USA

+1 703-578-2710

jdoherty@ida.org

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