From Marconi to GPS
A short (expurgated)*
History of Radio Navigation
(with a few Capricious excursions by the Speaker)

With much credit to Internet research, especially Wikipedia

Bradford Parkinson
Stanford University

* Focus on US systems - there is a huge body of history for foreign systems - German, British, Russian, French, etc.
Outline

• RF Pioneers – Maxwell and Marconi
• Definitions
• Jimmy Doolittle's demonstration
• Early Systems
• First Worldwide System (s)
• Second Worldwide System
• Third Worldwide System
• A Few Observations
Theoretical Basis:

James Maxwell  (1831-1879)

- Discovered the equations that govern the propagation of electromagnetic waves through space.
- This theory explained the first Transatlantic Radio Transmission by Guglielmo Marconi (Probably not well understood at the time!)

1868 Version (Integral Form)

\[ \iiint E \cdot dA = \frac{q}{\varepsilon_0} \]
\[ \iiint B \cdot dA = 0 \]
\[ \int E \cdot ds = -\frac{d\Phi_B}{dt} \]
\[ \int B \cdot ds = \mu_0 i + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} \]

1. \( \nabla \cdot D = \rho_v \)
2. \( \nabla \cdot B = 0 \)
3. \( \nabla \times E = -\frac{\partial B}{\partial t} \)
4. \( \nabla \times H = \frac{\partial D}{\partial t} + J \)
Italian inventor and engineer

Guglielmo Marconi (1874-1937)

Statue in Washington DC at Lamont and 16th Street
(Courtesy Google Street View!!!)

- Experimentalist in wireless telegraphy
  (1st patent in England 1896)
- Developed the first effective system of radio communication
- First transatlantic wireless transmission (12 Dec. 1901)
- Unknown to Marconi, the Ionosphere played an essential role in long range transmissions
- His invention Initially deployed in Ships
  - Instrumental in catching a fleeing murderer on trans-Atlantic voyage in 1910 (“Thunderstruck”)
  - Enabler for rapid rescue of Titanic Victims (14 April 1912)
- Proposed Other uses of Radio Waves

Marconi: The Man Who Networked the World  Jul 27, 2016 by Marc Raboy
Nobel Prize for Physics 1909

Awarded to Gugliermo Marconi and Ferdinand Braun

- Braun invented CRT. He then became interested in wireless technology.
- Italian inventor Guglielmo Marconi had conducted the first successful wireless transmission in 1895, but antenna was directly in the power circuit so broadcasting was inefficient and limited in range.
- Braun solved this problem by producing a sparkless antenna circuit. It linked transmitter power to antenna circuit inductively, greatly increasing the broadcasting range of a transmitter.
- Braun's discovery enabled Marconi to conduct the first transatlantic transmission in 1901
- Ultimately led to the formation of the wireless technology industry.

In 1909, Braun and Marconi were jointly awarded the Nobel Prize in Physics for their pioneering developments in the field.
Marconi - a few samples...

Lecture to IEEE 1901:
“I have built very largely on the work of others...I would like to mention Clerk Maxwell, Lord Kelvin, Professor Henry and Professor Hertz...”

Lecture to IEEE in 1922 Anticipated Radar:
“...it should be possible to design apparatus by means of which a ship could radiate or project a divergent beam of these rays in any desired direction, which rays, if coming across a metallic object, such as another steamer or ship, would be reflected back to a receiver screened from the local transmitter on the sending ship, and thereby immediately reveal the presence and bearing of the other ship in fog or thick weather.”
Should **Californian** have gone to rescue?

Twelve Ships received distress call...

Wireless operators originally used Marconi's "CQD" distress signal. "CQ" was the signal to stop transmission and pay attention. The "D" was added to signal distress.
Should **Californian** have gone to rescue?

- The **Californian** radioed **Titanic** 19:00 hours, to warn of an ice field, the **Californian** nearly collided with herself.
- Captain Stanley Lord ordered **Californian** to stop for night - too dangerous to proceed. Spotted **Titanic's** lights about 5 miles away.
- **Californian** radioed **Titanic** again, warning: "stopped and surrounded by ice." The radio signal was so strong, it interrupted Titanic's regular communication - reply was "Shut Up. Shut Up. I am Busy." **Californian** shut down its wireless at 23:30, Titanic struck the iceberg ten minutes later.
- **Californian** was sighted from **Titanic's** bridge 25 minutes later and distress rockets were fired.
- Officers aboard **Californian** spotted several rockets and called down to Captain Lord, who had gone to bed.
- Lord suggested **Californian** contact **Titanic** via morse lamp. Did not wake the wireless operator. Suggested rockets were company signals Some of **Californian's** officers believed there was a more serious nature behind the rockets.
- At 0200, **Titanic** appeared to "be leaving the area" after firing a total of eight white rockets. This was reported to Captain Lord who did nothing. Titanic sank at 0220 hours.
- At 0300, officers of the **Californian** sighted rockets coming from the south. From RMS **Carpathia** who had traveled all night towards **Titanic**.
- At 0416, A shift change resulted in **Californian's** wireless operator to inquire about why a ship had fired rockets earlier.
- At 0530, Captain Lord, now awake, ordered the **Californian** to **Titanic's** position. But through a twisted, longer, route instead of directly there.
- **Californian** arrives alongside Carpathia who just finished collecting all survivors. After Carpathia departs for New York, **Californian** stays behind to continue the search only to find wreckage.

The conclusions of two Inquiries officially placed blame on Captain Stanley Lord of the SS **Californian** for his inaction of the disaster, a verdict that officially ruined both his career and his life. **Californian torpedoed in 1915 and its fate was never determined**
Marconi Microwave Beam Steering Demonstration - Summer 1934

- Sestri Levante, Italy
- Noted as a particularly narrow channel approach
- Invited British and Italian maritime experts
- Totally curtained Pilothouse
- Apparently Marconi did not pursue this application

Note Issue of “Fly-to” versus “Fly-from”
A Few Definitions

Radio Determination

Radio Navigation generally: measurements from/to RF Beacons

Radio Navigation:
- Distances, e.g. ranging by measurement of travel times
- Directions, e.g. by bearing, radio phases or interferometry
- Partly also velocity, e.g. by means of radio Doppler shift

Radio Location
- e.g.
  - Radar
  - Cell phone Location (E911)
  - Buried Cables
  - etc.
Categories of Radio Navigation Systems

1. **Bearing Measurement**, e.g. RDF
   - User determines relative direction from his location to a known transmitter location (also used as a radio-location system).

2. **Beam Steering**, e.g. VOR
   - User can determine which azimuthal sector one is in relative to a transmitter.

3. **Transponder**, e.g. DME
   - User determines range to a known location with roundtrip travel time. Inverse process is used by ATC to locate and identify aircraft (IFF).

4. **Hyperbolic two dimensional**, e.g. Loran, Omega (Use of Master Pulse)
   - User determines location on a number of hyperbolic LOPs by measuring TDOA to pairs of time-synchronized transmitters.

5. **Psuedo-Range**, e.g. GPS (System Synchronized Time)
   - User measures time of ≥ d+1 incoming signals with user clock - with (d+1) measurements, where d is dimensionality [2 or 3] and the extra measurement calibrates the user’s clock in “system time” - closely related to category 4.

Reminder: A hyperbola is a set of all points P such that the difference between the distances from P to the foci, $F_1$ and $F_2$, are a constant K.
Radio Direction Finding - RDF
- a device for finding the direction, or bearing, to a radio source

- Hertz (1888) discovered directionality
- Major area of research in early 1900s
- Operational Prototype Tested by Army Air Corps in 1931
- Two measurements of known transmitter locations determine position
- Receiving antennas ~ proportional to wavelength - usually require at least $\frac{1}{4}$ wavelength (usually $\frac{1}{2}$)
  - Suggests higher frequency, but shorter range
  - Initially mechanically rotated
  - Now “automatic” - ADF - and exploits AM radio stations
Dr. James Doolittle

4 star Gen USA (1896 - 1993)

- BA Cal 1922
- MS Aero MIT 1924
- 1927 First to perform an outside loop
- 1932 World’s high speed record
- Won Thompson Trophy race in Gee Bee R-1

- PhD received in June 1925. His doctorate in aeronautical engineering was the first ever issued in the United States.

- In 1929, he became the first pilot to take off, fly and land an airplane using instruments alone
What is going on here?
Doolittle’s Blind Flying Achievement -  
Sponsored by US Army

• Instruments:
  ▪ newly developed Kollsman Altimeter
  ▪ Sperry Directional Gyro and Artificial Horizon
  ▪ Radio range and marker beacon developed by the Bureau of Standards
  ▪ Special radio receiver with a vibrating reed display built by the Radio Frequency Laboratories
Mail Pilots who had flown with both aural and visual systems strongly preferred the visual type. Reed-based solution was passed over by the U.S. government, Audio signals became standard for decades to come.\[1\]

The low-frequency radio range (LFR), also known as the four-course radio range, LF/MF four-course radio range, A-N radio range, Adcock radio range, or commonly "the range", was the main navigation system used by aircraft for instrument flying in the 1930s and 1940s, until the advent of the VHF omnidirectional range (VOR), beginning in the late 1940s.

• Mail Pilots who had flown with both aural and visual systems strongly preferred the visual type. Reed-based solution was passed over by the U.S. government, Audio signals became standard for decades to come.\[1\]
Original Low-Frequency Radio Range (LFR) station based on crossed loop antennas

- Development and testing of the AN range system completed February 1928
  - Demonstration flight from Newark/New York to Cleveland, Ohio,
  - Three AN range ground stations- New Brunswick NJ, Bellefonte PA, and Cleveland OH.

Mature System: Adcock range station had four 134-foot-tall (41 m) antenna towers
Examples

(See Wikipedia: Media help if you encounter problems playing these sound files.)
LFR (Low-frequency Radio Range) - Early Mainstay for Radio Nav in US

- At its peak there were nearly 400 LFRs
- 190 to 535 kHz and 1,500 watts
- Four “quadrants” - not necessarily orthogonal

Also Called:
- Adcock radio range
  Invented by Frank Adcock of the British Army 1919
- Four-course radio range,
- LF/MF four-course radio range,
- A-N radio range,

Limitations:
- Course lines affected by weather and snow on ground
- Only four “directions”
- Pilot had to listen for hours
- Quadrants sometimes skipped
- Susceptible to interference - “storms and static could make it almost useless”
Low Frequency Radio Range (LFR)

The Sector with the north azimuthal radial was always broadcast as “N”
The 12 Course Radio Range System (1929 by National Bureau of Standards)

- Directions could be modified to line up with runways
- Experimental - apparently never deployed
Parallel Development - German “Lorenz” system \textbf{(1932)}

Developed by Joseph Plendl (1900-1991)

- “Ultra” short wave system (33.33 MHz)
- Three feeds – Left and Right alternately short-circuited
- Assymetrical duty-cycle gave left and right
- Created a much narrower beam center than a single beam of same size (1/3 of a degree - 1 mile at 200 miles)
- Installation include marker beacons at 300m and 3 km.
- First Installed in Tempelhof in 1932
- Led to a number of German WWII Blind Bombing Aids
Non-directional beacons (NDBs)

• From early 1930s, LFR augmented with Low Frequency Non-directional beacons (NDBs).

• LFR - complex ground installation
  • simple AM receiver on board the aircraft

• NDB ground installations - simple single-antenna transmitters
  • More complex equipment on board the aircraft.
Loran/Decca/Gee Hyperbolic systems (TDOA)

• Central Master and at least two “slaves”
  • Slaves receive master signal and synchronize with a fixed delay

• Origins of Loran – “Gee”
  • First Proposed in October 1937, by Robert (Bob) J. Dippy,
  • Initially a short-range bombing and Landing aid in Europe
  • He later was an advisor to US on LORAN A

Bob Dippy - Worked at Robert Watson-Watt's radar laboratory at RAF Bawdsey
Hyperbolic Systems - Principal of Operation

A and B - transmitting stations
Curved lines - “TD” lines or Time Difference

LOP - The locus of all positions where the observed time difference between the arrival of signals from two stations are constant.

The LOP forms a hyperbola which gives rise to the designation of Loran-C as a hyperbolic radionavigation system.
Loran/Decca/GEE

• Hyperbolic Systems with TDOA measurements
• US beginnings 1940 30 MHz down to 3 MHz (Army Signal Corps - Alfred Loomis)
• Cumbersome delta time measurements using CRTs
• Adopted GEE and sought a long range version - changed to 1.85 MHz
• First Chain June 1942, by end of 1943 over 12 around North Atlantic.
Loran must account for Phase lag associated with Earth and Sea conductivity.

Over salt water – fairly predictable
Over land (Mountains, water content etc.) can be variable

**Figure 2: Loran phase lag**
VHF Omni-directional Range - VOR

- very high frequency (VHF) band from 108 to 117.95 MHz
- developed in the United States beginning in 1937 and deployed by 1946
- Worldwide Aviation Standard
- By 2000 there were about 3,000 VOR stations around the world including 1,033 in the US, reduced to 967 by 2013 with more stations being decommissioned with the widespread adoption of GPS.
VOR Operation

- Two Signals
  - Omindirectional Master – gives north timing “pulse” (actually an FM broadcast)
  - Phased Array rotating 30 times/second clockwise from north (the AM broadcast)
- Can Include voice broadcasts
- US FAA plans by 2020 to decommission ~half of the 967 US VOR stations, retaining a "Minimum Operational Network"
  - Frequently co-located with DME
  - Similar to Military “TACAN”
VOR Accuracy

• test data indicate that 99.94% of the time a VOR system has less than ±0.35° of error - about 0.6 nm at 100 nm.
• Self monitored for accuracy
Aircraft interrogates ground transponder w/series of pulse-pairs

After a precise time delay (typically 50 microseconds), the ground station replies with identical sequence.

DME receiver in the aircraft searches for reply pulse-pairs

In track mode, 30 interrogations/sec

Accuracy of DME is ~185 m (±0.1 nmi).

Can handle up to 200 aircraft at once

Distance Measuring Equipment - DME (both civil and military)

- Transponder-based radio navigation technology
- Measures slant range distance by timing the Round-trip propagation delay of VHF or UHF radio signals.
TACAN - military VOR+DME

- **Frequency** band 960-1215 MHz. (UHF)
- Bearing info at least 3 times better than VOR
- A VORTAC - VOR for civil bearing information and a TACAN for military bearing information and military/civil distance measuring information
Instrument Landing System

“provides aircraft with horizontal and vertical guidance just before and during landing”

- Pairs of Transmitters called **Localizer** (Azimuth) and **Glide Slope**
- CAA Testing began in 1929
- First civil landing 1936
- By 1945, 9 systems installed and US Army introduced new higher frequency system
- In 1949, **ICAO adopted Army system** as standard
- “Fly to” needles in cockpit
- Still the dominate commercial landing system.
Transit - Navy Navigation Satellite System (NNSS)
The Source of **Basic Idea of Using Artificial Satellites for Terrestrial Navigation**

**The Dawn of Satellite Navigation**

The role of [John's Hopkins' Applied Physics Lab](#)

- 4 October 1957 - Sputnik is launched

- US Failures and success (31 January 1958)

- William Guier and George Weiffenbach (APL)
  - Sputnik Doppler Signature Unique
  - Single Pass Orbit Determination

- Frank McClure (APL) suggested inverting the problem (1959)
  - Using known satellite position solve for user's position

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Radio Navigation
Navy's Transit - NNSS
Navy Navigation Satellite System

- Developed 1960-64
  under Dick Kirschner - APL
- Purpose: Update Submarine
  Inertial Navigation Systems
- Doppler (Frequency-based) system
- Polar Orbits at 1075 km.
  (107 Min.)
Navy’s Transit - NNSS
Navy Navigation Satellite System

- Satellite
  - Solar Powered
  - Gravity Gradient Stabilized
  - Scout Launched
- 150 and 400 MHz (Iono Correction)
- Orbit determination and prediction - 12 hrs.
- Fix available every few hours

By 1964, Some felt an improved Satellite Navigation System could be Developed (24/7, 3-D, Worldwide system)...
- Velocity Correction: 1 knot = 0.2 n. mi.
The Eras of Satellite Navigation

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<td><strong>Pioneers - Transit</strong></td>
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<td>First Syst. Test</td>
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<tr>
<td>Transit Operational</td>
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<td>Operation Ceased</td>
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</table>
Omega 1971 to 1997 (similar to a UK system proposal DERLAC, proposed in 1954; Russians had system Alpha)

- Hyperbolic, Worldwide two dimensional (8 stations operational of 9 deployed)
- **VLF (10 to 14 kHz)** - Huge antennas (1200 to 1400 feet high)
- ~ One second pulses every 10 seconds
- Accuracy 3 to 6 miles
- In US managed by Coast Guard (+ Argentina, Norway, Liberia and France)
Originally Classified Secret and could not be discussed in Public

– Not declassified until 1979

6 years after GPS Definition

Jim Woodford
Aerospace Corp

Hiryoshi Nakamura
Aerospace Corp

Dr. Ivan Getting
President Aerospace Corporation

Dr. Ivan Getting
Parkinson 2016 SCPNT/Marconi History of Radio Navigation
The **Most Fundamental** Innovation of GPS - Spread-Spectrum (CDMA - PRN) for Passive Ranging

**Additional Advantages**

- Easily Encrypted
- Simplified Digital Sampling for User
  - One bit sampling is within 3 dB of Optimal
  - Anticipated the All - Digital Receiver
- **GPS Jam Resistance**
  - Processing “Gain” of spread spectrum (PRN) signal
  - Inertial aiding
  - Directional antennas
- **Selected during “Lonely Halls” meeting after competition with Timation/NRL’s Side-Tone Ranging**
### The Eras of Satellite Navigation

<table>
<thead>
<tr>
<th>Year</th>
<th>Event/Development</th>
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<tbody>
<tr>
<td>1960s</td>
<td>New Systems Proposed (mid 1960’s)</td>
</tr>
<tr>
<td>1960s</td>
<td>621B (USAF)</td>
</tr>
<tr>
<td>1960s</td>
<td>TIMATION (NAVY)</td>
</tr>
<tr>
<td>1960s</td>
<td>UPGRADED TRANSIT (NAVY)</td>
</tr>
<tr>
<td>1972</td>
<td>“Joint” Program Office (JPO) 1972</td>
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<td>1972</td>
<td>Director, Col. Parkinson</td>
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<tr>
<td>1973</td>
<td>“GPS” System Defined/ Labor Day 1973</td>
</tr>
<tr>
<td>1973</td>
<td>Development Approved / Dec 22, 1973</td>
</tr>
<tr>
<td>1995</td>
<td>GPS Operational April 1995 (21.4 yrs)</td>
</tr>
</tbody>
</table>

#### Pioneers -Transit
- D-1
- GPS-I
- IOC

#### Deployment and Applications Development

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11/8/16 Parkinson 2016 SCPNT/Marconi History of Radio Navigation
Aviation Example: Pathway in the Sky
(Enabled by Precision 3-D GPS - Pioneered by Dr. Andy Barrow)

- Pathway calculated as series of Pentagons
- Own Plane predicted position shown in center
- Intuitive projection of 3-D
- Especially suited for curving and dog-leg approaches
- Real data show errors reduced to 1/3 of best conventional technique
FAA Certified GPS Approaches

• As of October 13, 2016, there are 3,722 Wide Area Augmentation System (WAAS) Localizer Performance with Vertical guidance (LPV) approach procedures serving 1812 airports. 1058 of these airports are Non-ILS airports.

• Currently, there are also 621 Localizer Performance (LP) approach procedures in the U.S. serving 462 airports.
GPS/FANS based Tailored Arrivals – UAL HNL-SFO

True 4-D procedure “tailored” for flight using continuous descent

Average Fuel Saved (Boeing 747) = 1600 lbs!
(There are ~28,500 Commercial flights in the US per Day!!)

Payoffs:
- Better Safety
- Less Delays
- More Airways Capacity
- Smaller Fuel and Carbon Footprint

NextGen
- FAA Air Traffic Control for the Future
PNT to Explode with Opportunities

• Next generation 4 new Civil signals at two new frequencies

• 10 New Civil Signals - Included is a new *International Signal* called L1C
  • It will provide Interchangeability for *All Navigation Satellite Signals*

  • *And* there will be over 60 satellites on orbit!

*Result: Even Better Accuracy, Availability and Integrity*
eLoran System Overview (courtesy UrsaNav)

- Powerful Signal 100 kHz (up to 100kW)
- 2D
- In real-time calibrated area ~20m accuracy
2D Positioning with eLoran
(Courtesy UrsaNav)

Clock bias is common on all measured TOAs
Clock bias is solved in position iteration process
Three TOA measurements to solve three unknowns: Latitude, Longitude and Clock bias
Additional TOAs enable (weighted) least squares positioning

How is transmission time synchronized?
Some Final Observations

• History of Radio Navigation rich and varied over more than 100 years – Marconi was an early conceptualizer

• Non US contributions are also significant but:
  • Most international systems are traceable to US initial Operation but also
  • Many other countries invented or developed basic concepts and technology

• Largest investor in Radio Navigation research and development has been the Military

• Aside: GPS is great, but we still need to PTA
Thank You
## Satellite Navigation Systems

<table>
<thead>
<tr>
<th>System</th>
<th>GPS</th>
<th>GLONASS</th>
<th>Galileo</th>
<th>BeiDou</th>
<th>IRNSS</th>
<th>QZSS</th>
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</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>GNSS</td>
<td>RNSS</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Provider</strong></td>
<td>United States</td>
<td>Russian Federation</td>
<td>European Union</td>
<td>China</td>
<td>India</td>
<td>Japan</td>
</tr>
<tr>
<td><strong>Fully operational</strong></td>
<td>1995</td>
<td>2011</td>
<td>2020</td>
<td>2017</td>
<td></td>
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<tr>
<td><strong>Code structure</strong></td>
<td>CDMA</td>
<td>FDMA CDMA (GLONASS K)</td>
<td>CDMA</td>
<td></td>
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<tr>
<td><strong>Orbital altitude</strong></td>
<td>20,180 km</td>
<td>19,130 km</td>
<td>23,222 km</td>
<td>21,520 km &amp; 35,786 km</td>
<td>35,786 km</td>
<td>35,786 km</td>
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<tr>
<td><strong>Period</strong></td>
<td>11 h 58 min</td>
<td>11 h 16 min</td>
<td>14 h 5 min</td>
<td>12 h 53 min &amp; 23 h 56 min</td>
<td>23 h 56 min</td>
<td>23 h 56 min</td>
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<tr>
<td><strong>Revs/sidereal day</strong></td>
<td>2</td>
<td>17/8</td>
<td>17/10</td>
<td>13/7 &amp; 1</td>
<td>1</td>
<td>1</td>
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<tr>
<td><strong>Repeat period (sidereal days)</strong></td>
<td>1</td>
<td>8</td>
<td>10</td>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Number of satellites</strong></td>
<td>Nominal 24 (IIA, IIR, IIRM, IIF, III)</td>
<td>28 (at least 24 by design- M, K1, K2)</td>
<td>4 exp. 8 operational in orbit Plan: 30 MEOs</td>
<td>Currently 14 Planned 5 GEOs 3 IGSO 27 MEOs</td>
<td>3 GEOs 4 IGSOs</td>
<td>Currently 1 IGSO Planned 3 IGSOs 2 GEOs</td>
</tr>
<tr>
<td><strong>Frequencies</strong></td>
<td>See Chapter 2 in this book</td>
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<tr>
<td><strong>Status</strong></td>
<td>Operational</td>
<td>Operational</td>
<td>In preparation</td>
<td>19 operational, 40 additional 2016-2020</td>
<td>7 launched</td>
<td>Himawari-9 planned in 2016</td>
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Global Positioning & Timing Service (GNSS)
Differential eLoran
Improves Accuracy in a limited region

The Maritime Service Provider is responsible for generating the Diff Loran Corrections and providing Signal Propagation Maps.

10 to 20 Meter Accuracy is claimed
Basic eLoran Equation for $i$th Range Measurement (Very similar to GPS range equation)

- **Great Circle Range to Transmitter** – Needed to determine Position
- **User Clock Error** – common to all measurements
- **Actual error** in Measurement and the three “Factors”
  - **Standard Adjustment** for signal delay of *Atmosphere* – “Primary Factor”
  - **Additional Tailored Adjustment** for particular signal path over terrain “Additional Secondary Factor”
  - **Standard Adjustment** for signal delay at *Sea Level over Salt Water* “Secondary Factor”

Measured Time of Arrival