NAVIGATION: LAND, SEA, AIR, SPACE

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NAVIGATION OVERVIEW

- **LAND:**
  - **SLOW, SHORT RANGE**
  - **ALTITUDE KNOWN FROM MAPS**
  - **OFTEN CONFINED TO ROADS: CITY AND HIGHWAY**
  - **OFF-ROAD: RAILROAD**
  - **SEVERE TEMPERATURE and VIBRATION**

- **SEA:**
  - **SLOW, WORLD-WIDE**
  - **NEAR-GREAT-CIRCLE ROUTES IN SEA LANES**
  - **ALTITUDE = 0 AT SEA, FROM MAPS IN RIVERS**
  - **SEVERE SALT, WATER, TEMPERATURE, PITCH-ROLL**

- **AIR:**
  - **SPEED < TRIPLE EARTH RATE, WORLD-WIDE**
  - **GREAT-CIRCLE ROUTES, CIVIL AIRWAYS**
  - **SPECIAL MILITARY MISSIONS: TERRAIN-FOLLOWING**
  - **ALTITUDE MEASUREMENTS REQUIRED**
  - **USUALLY OPERATE FROM SURVEYED AIRPORTS**

- **SPACE:**
  - **BOOST, ORBITAL, INTERPLANETARY, ENTRY**
  - **NAVAIDS HAVE BEEN PRIMARILY GROUND-BASED**
  - **GPS AND TDRS SPACE-BASED**
  - **SOME CALCULATE ON-BOARD, SOME MEASURE ON-BOARD**
  - **VACUUM, CORONA-DISCHARGE, RADIATION BELTS**
  - **LAUNCH ACCELERATION**

ATTRIBUTES OF NAVIGATION SYSTEMS

1. COST

2. ACCURACY

3. AUTONOMY

4. TIME DELAY

5. GEOGRAPHIC COVERAGE

6. AUTOMATION

7. ENVIRONMENT

NAVIGATION ATTRIBUTES -2

ENVIRONMENT

- **AUTOMOBILES:**
  - **-40C TO +125C IN ENGINE COMPARTMENT**
  - **TEMPERATURE CYCLING**
  - **ELECTRIC POWER SURGES AND OUTAGES**

- **AIRCRAFT:**
  - **LOW PRESSURE**
  - **TEMPERATURE AND TEMPERATURE CYCLING**
  - **OFTEN CLIMATE-CONTROLLED**
  - **GUN RECOIL SHOCK AND VIBRATION**
  - **AIR TURBULENCE AND HARD LANDINGS**
  - **ELECTRIC POWER TRANSFERS FROM BUS TO BUS**

- **SPACECRAFT:**
  - **VACUUM**
  - **TEMPERATURE CYCLING**
  - **COSMIC RAY "SINGLE-EVENT UPSETS“**
  - **VAN ALLEN BELTS**
  - **LAUNCH VIBRATION**

- **SHIPS:**
  - **SALT WATER**
  - **LOW-FREQUENCY VIBRATION**
  - **LARGE-AMPLITUDE ANGULAR MOTIONS**

GUIDANCE vs. NAVIGATION

- **NAVIGATION DETERMINES STATE VECTOR:**
  - **3 COMPONENTS OF POSITION**
  - **3 COMPONENTS OF VELOCITY**

- **NAVIGATION AND GUIDANCE:**
  - **CALCULATES DISTANCE AND DIRECTION TO DESIRED POSITION**
  - **GREAT CIRCLE CALCULATIONS, AIRWAY STEERING**
  - **FLEXIBLE ROUTES**

- **HOMING GUIDANCE:**
  - **STEER AND THRUST TOWARD TARGET WITHOUT STATE VECTOR**
  - **AIM AT TARGET OR LEAD AHEAD OF IT**
  - **WILL EVENTUALLY COLLIDE USING PROPORTIONAL NAVIGATION**
  - **TYPICAL OF HOMING MISSILES**
    - **RADAR, LASER, INFRA-RED GUIDANCE**
    - **MANEUVER LIMITS, CONTROL LIMITS**

- **BASIS OF NAVAIDS:**
  - **VOR, ILS**
  - **CHEAP, WORKS BEST NEAR NULL**

ABSOLUTE FIX vs. DEAD-RECKONING

- **ABSOLUTE FIX:**
  - **VIA RADIO, VISUAL SIGHTING, MAP-MATCHING**
  - **INDEPENDENT OF PAST TRAJECTORY**
  - **MEASURE RANGE OR TIME-DIFFERENCE**
  - **VELOCITY FROM DOPPLER OR CALCULATED**

- **DEAD – RECKONING:**
  - **MEASURE VELOCITY, ACCELERATION, DISTANCE**
    - **INCREMENTS**
    - **HEADING**
  - **ITEGRATE TO OBTAIN CURRENT POSITION, VELOCITY**
  - **NEED INITIAL ABSOLUTE FIX**
  - **POSITION IS LOST IN CASE OF FAILURE, POWER OUTAGE**

DEAD-RECKONING

- **MEASURE DISTANCE/SPEED:**
  - **SHIP'S LOG**
    - **IMPACT PRESSURE OR ELECTRO-MAGNETIC**
  - **ODOMETER**
  - **AIRSPEED**
    - **PITOT-TUBE**
    - **MULTI-PORT**
  - **DOPPLER RADAR**
  - **DOPPLER SONAR**

- **MEASURE HEADING:**
  - **MAGNETIC COMPASS**
  - **GYROCOMPASS**
  - **DIFFERENTIAL ODOMETER**

- **COMPUTATION:**
  - **RESOLVE INTO NAV COORDINATES AND INTEGRATE**
  - **FLAT EARTH, SPHERICAL EARTH, ELLIPSOIDAL EARTH**
  - **STEERING TO WAYPOINTS**

- **INERTIAL NAVIGATOR IS THE MOST PRECISE DEAD-RECKONING**

NAVIGATION RADIO FREQUENCIES

- **10-13 KHz** **OMEGA**
- **70-130 KHz** **LORAN-C, DECCA**
- **200-2000 KHz** **A-N RANGES (1930-50)**
  BROADCAST DF
  MARINE HF/DF
  CONSOLAN

- **2 MHz** **LORAN-A**
- **75 MHz** **MARKER BEACONS FOR ILS, FORMERLY AIRWAYS**
- **100-120 MHz** **VOR, ILS LOCALIZER**
- **150** **TRANSIT**
- **300** **ILS GLIDE SLOPE, SHORAN**
- **400** **TRANSIT, PLRS**
- **1000-1200 MHz** **DME; TACAN BEARING**
  GPS, IFF, JTIDS

- **2-3 GHz** **S-BAND COMM-TRACKING (SPACE)**
- **4 GHz** **C-BAND RADAR (SPACE)**
- **5 GHz** **MICROWAVE LANDING SYSTEM**
- **10 GHz** **X-BAND RADAR**
- **20 GHZ** **K-BAND RADAR**

- **10 Hz** **INFRA-RED SENSORS**
- **10 Hz** **VISIBLE LIGHT**
- **10 Hz** **ULTRA-VIOLET LASERS**

APPROXIMATE ACCURACY OF NAVIGATION (one standard deviation)

- **3 CM:** DIFFERENTIAL GPS SURVEY
- **10 CM:** THEODOLITE-GEODIMETER SURVEY
- **3 METERS:** LOW-ORBIT DETERMINATION
  MAPPING RADAR
  ILS NEAR TOUCHDOWN
  DIFFERENTIAL GPS, MOVING
- **30 METERS:** GPS (MILITARY BETTER, CIVIL WORSE)
  TDRS
  APOLLO SPACETRACK
  ASTRO-INERTIAL NAVIGATION
  DECCA
- **300 METERS:** LORAN C
- **3,000 METERS:** CORRECTED OMEGA
  BEST CELESTIAL NAVIGATION AT SEA
- **30,000 M:** NON-UPDATED INERTIAL NAVIGATION, AFTER 10 HRS
  UNCORRECTED OMEGA
  DEAD-RECKONING AT SEA, LOG AND COMPASS

TIME REQUIREMENTS FOR NAVIGATION

1. INTERVAL MEASUREMENT:

- **Start clock at one event**
- **Stop clock at another event**
- **ACCURACY**
  - **oscillator circuit, R-L-C** **10E2 to 10E3**
  - **analog wristwatch** **10E4**
  - **pendulum clock, stationary** **10E6**
  - **quartz crystal oscillator**
    - **30 MHz** **10E6 to 10E7**
    - **300 MHz** **10E5 to 10E6**
    - **temperature-compensated (TXO)** **10E6 to 10E9**
    - **oven-controlled (OXO)** **10E7 to 10E10**
  - **Rubidium oscillator** **10E11 to 10E12**
  - **Cesium oscillator** **10E13 to 10E14**

2. ABSOLUTE TIME:

- **Clock at specific location, after arbitrary event**
  - **clock exchange programs before 1990**
  - **signal exchange programs via GPS**

GLOBAL POSITIONING SYSTEM (GPS)- 1

- **SATELLITES:**
  - **SINCE 1995, 21 + 3 SATELLITES; 4 OR MORE IN VIEW ANYWHERE ON SURFACE OF EARTH**
  - **12-HOUR ORBITS AT 26,560 KM, 6 PLANES AT 55-DEG INCLIN**
  - **GROUND MONITOR AND CONTROL STATIONS**
  - **DEVELOPED AND OPERATED BY U.S. DEPARTMENT OF DEFENSE**
  - **OTHER NAVAIDS TRANSITIONED TO U.S. COAST GUARD**
  - **EPOCH DATES 5 JAN 1980, 22 AUGUST 1999, APRIL 2019**
  - **SOVIET GLONASS SIMILAR BUT NOT COMPATIBLE**
    - **EACH SATELLITE ON OWN FREQUENCY**
    - **512-BIT C/A CODE**
    - **L2/L1 = 1.2857 VS 9/7 FOR GPS**
    - **7 USABLE SATELLITES 11/02**

- **SATELLITE TRANSMITTER:**
  - **3-4 CESIUM OR RUBIDIUM CLOCKS, 10E13 STABILITY**
  - **ALL SATS BROADCAST ON SAME TWO FREQUENCIES**
    - **L1 = 1575.42 MHZ**
    - **L2 = 1227.60 MHZ**
    - **MODULATION OF CARRIER IS QPSK**
  - **MODULATION ON L1**
    - **1.023 MBPS C/A-CODE, 1024 BITS LONG**
    - **10.23 MBPS CLEAR P-CODE OR ENCRYPTED Y-CODE**
    - **CODE LENGTH IS ONE WEEK**
    - **EACH SAT USES ONE OF 42 ORTHOGONAL CHIPPING CODES**
    - **50 BPS DATA: EPHEMERIS, ALMANAC, STATUS, TIME**

GLOBAL POSITIONING SYSTEM (GPS)- 2

- **3-SATELLITE FIX:**
  - **SOLVE FOR HORIZONTAL POSITION IF HEIGHT KNOWN**
  - **CORRECT THE OFFSET OF USER'S CLOCK**
  - **2-POINT AMBIGUITY**
  - **LESS THAN: 25 METERS RMS RANGE ERROR, L1**
    10 METERS WITH L1/L2 IONOSPHERIC CORRECTION

- **4 OR MORE SATELLITES:**
  - **SOLVE FOR 3-AXIS POSITION**
  - **CORRECT THE OFFSET OF USER'S CLOCK**
  - **5-15 METER ERROR WITH P- OR Y-CODE**

- **RECEIVER QUALITY"**
  - **CLOCK STABILITY**
  - **NUMBER OF PARALLEL CORRELATORS**
  - **CARRIER TRACK VS CODE TRACK: L1, L2, L5**
  - **ANTENNA: ISOLATION FROM CIRCUIT BOARD**
  - **PRE-AMPLIFIER: BANDWIDTH, FIELD OF VIEW, ADAPTIVE**
  - **EXTENT OF USE OF DOWNLINKED DATA**
  - **IONOSPHERIC CORRECTION**

- **DIFFERENTIAL GPS:**
  - **CENTIMETER TO 10-METER ERROR WITH C/A CODE, DEPENDING ON DISTANCE FROM MONITOR STATION AND DURATION OF OBSERVATIONS**

DIFFERENTIAL GPS - 1

- **BASE STATION:**
  - **KNOWN POSITION**
  - **MEASURES RANGES TO VISIBLE GPS SATELLITES**
  - **TRANSMITS RANGE OFFSETS FROM EACH SATELLITE**

- **REMOTE STATION = VEHICLE:**
  - **MEASURES RANGE USING SAME SATELLITES**
  - **CORRECTS FOR OFFSETS**
  - **CALCULATES PRECISE STATE VECTOR**

- **ERROR SOURCES:**
  - **ATMOSPHERIC SPATIAL DIVERSITY**
  - **MULTIPATH**
  - **IMPROPER TRANSMISSIONS FROM A SATELLITE**
  - **EPHEMERIS**
  - **SPACE-BORNE ATOMIC CLOCK**

- **ATTITUDE MEASUREMENT WITH DGPS:**
  - **3 OR MORE ANTENNAS ON RIGID BODY**
  - **ALL TRACK SAME SATELLITES**
  - **MEASURE ATTITUDE TO 10+ arcsec**
  - **PHASE-CENTER UNCERTAINTY OF ANTENNAS**

DIFFERENTIAL GPS - 2

- **SURVEY WITH DGPS:**
  - **CENTIMETER ACCURACY FOR A MINUTE'S DWELL TIME**
  - **~20 km MAXIMUM SEPARATION**

- **WAAS:**
  - **NATIONWIDE U.S. NETWORK OF AERO BASE STATIONS**
    - **EACH TRANSMITS RANGING ERRORS TO COM-SATELLITES**
    - **COMSATS REBROADCAST ON VHF RADIO PER RTCA SC-159**
    - **EN-ROUTE AIRCRAFT NAVIGATE DIFFERENTIALLY**
    - **AIRCRAFT LAND DIFFERENTIALLY**
      - NON-PRECISION
      - CATEGORY I
      - BAROMETRIC ALTITUDE
  - **SHIPS ENTERING PORT NAVIGATE DIFFERENTIALLY**
    - **RTCM STANDARD SC-104 AT 290-310 kHz**
    - **IN OPERATION BY U.S. AND CANADIAN COAST GUARDS**
  - **ERROR 1-5 METERS WITHIN 300 KM OF BASE STATION**
  - **LIKELY TO REPLACE VOR NETWORK**
  - **BASE STATION: DETECT AND BROADCAST SATELLITE FAILURES**
  - **ON VEHICLE: FLAG ERRORS, RESELECT SATS, ABORT LANDING**
  - **PRIVATE SUBSCRIPTION WAAS EXIST 2001**

DIFFERENTIAL GPS - 3

- **LAAS:**
  - **LOCAL U.S. NETWORK OF BASE STATIONS AT AIRPORTS**
    - **MAY INCLUDE PSEUDOLITES AT EACH AIRPORT**
    - **DETECT AND BROADCAST SATELLITE FAILURES**
  - **AIRCRAFT LAND TO CATEGORY II AND III**
  - **ERROR 1-3 METERS WITH INERTIAL SMOOTHING AND FAST COMPUTER**
  - **LIKELY TO REPLACE ILS AND MLS**
    - **ILS RETAINED AS LAAS MONITOR?**
  - **ON-BOARD:**
    - **LANDING AND ROLL-OUT WITHOUT FAILED SATELLITES**
    - **FAULT DETECTION AND RECONFIGURATION**
    - **CONTINUE NAVIGATION DESPITE FAULTS**

CELL PHONE POSITIONING (E-911)

PROBLEM: 1- EMERGENCY SERVICES CAN'T FIND CELL PHONES
2- CELL COMPANIES WANT TO SELL LOCATION SERVICE

U.S. GOVERNMENT MANDATE IN 1996:

- **LOCATE CELL PHONES WITHIN 50-100 METERS**
- **MANY DEADLINES, LATEST 2005**

SOLUTIONS:

1. REPORT NEAREST BASE STATION.
   - WIDELY IMPLEMENTED
   - ACCURATE IN CITIES
   - INDOOR MICROCELLS, WiFi

2. GPS IN EACH CELL PHONE
   - REPORT POSITION WHEN CALLED
   - USER CAN DISABLE REPORTS

3. TRIANGULATE FROM BASE STATIONS
   - USE UPLINK MESSAGES SOFTWARE IN CENTRAL OFFICE
   - USE DOWNLINK MESSAGES SOFTWARE IN CELL PHONE

4. TRIANGULATE FROM RADIO OR TV STATIONS
   - GOOD CLOCKS IN TV AND CELL PHONE
   - USE FLYBACK PATTERN
   - REPORT WHEN CALLED
   - USER CAN DISABLE REPORTS

5. TIME DIFFERENCES FROM BASE STATIONS OR CELL PHONE
   - SEND LORAN-LIKE PULSES
   - MEASURE DIFFERENCES IN TIMES OF ARRIVAL
   - OTHER PARTY CALCULATES POSITION ON MAP

6. INDOOR PROBLEM
   - PSEUDOLITE ON EACH FLOOR ALLOWS PRECISE LOCATION
   - GPS REPEATER LOCATES TO A BUILDING

UTILIZATION OF TEST DATA

- **SYSTEM SPECIFICATION:**
  - **BASIS FOR TESTS**

- **DATA COLLECTION:**
  - **DEFINE ROUTE TRAVELLED**
  - **SELECT POSITION AND VELOCITY REFERENCE**

- **WHICH DATA ARE DISCARDED?:**
  - **TEST EQUIPMENT ERRORS**
  - **"WILD POINTS"**
  - **HUMAN ERROR**

- **ERROR BUDGET:**

- **COST OF TESTS:**

- **TEST UNIT VERSUS PRODUCTION UNITS:**
  - **HOW TO IDENTIFY DIFFERENCES?**
  - **ARE RE-TESTS NEEDED?**

ANIMAL NAVIGATION

- **GOALS:**
  - **FIND WEATHER, FOOD, MATES**
  - **ADAPT TO PRECESSION OF EQUINOXES, MIGRATION OF POLES, REVERSALS OF MAGNETIC FIELD, ICE AGES**

- **SENSORS:**
  - **TERRAIN, LANDMARKS, DRIFT ANGLE?, GROUND SPEED?**
  - **ODORS**
  - **HEADING BY SUN**
  - **ELEVATION OF SUN = LATITUDE**
  - **POLES OF NIGHT SKY**
  - **MAGNETIC FIELD ?**
  - **VISCERAL VERTICAL**
  - **LOW-FREQUENCY SOUND?**
  - **POLARIZED LIGHT? ANT EXPERIMENTS**

- **PROCESSING:**
  - **NEURAL-NET PROCESSOR, WIRED EXPERT RULES**
    - **SOME DATA INHERITED, SOME LEARNED**
  - **LEARN BY FOLLOWING OLDER BIRDS**
  - **NO DETAILS KNOWN; BIRDS SEARCH, THEN ROOST ANEW**

- **TESTS - 30-YEARS' WORTH:**
  - **CAGES, PLANETARIA, HELMHOLZ COILS, HOMING**
  - **NATURAL OBSERVATIONS, RADAR AND BANDING**
  - **MANY ARE LOST ON LONG MIGRATIONS**

FUTURE OF NAVIGATION -1

1. NAVIGATION AND SURVEYING MERGE:

- SAME SENSORS
- DIFFERENT OBSERVATION DURATIONS
- DIFFERENT PROCESSING

2. GPS:

- FOR ALL VEHICLES
- ABSOLUTE AND DIFFERENTIAL NAVIGATION
- CHEAP AND EXPENSIVE RECEIVERS
- DELIBERATELY-SPOILED ACCURACY ON C/A CODE
  - WAS SUSPENDED IN 2000
- GPS-GLONASS RECEIVERS

3. CIVIL RADIO AIDS:

- MANY WILL BE DECOMMISSIONED
  - OMEGA DECOMMISSIONED 11/97
  - LORAN, VOR, ILS DECOMMISSIONED IN 2010s??
- BIG GROWTH IN TCAS AND MODE-S
- MULTISENSOR RECEIVERS, FALLING PRICES
- 4-d TUBES IN SPACE WITH ESCAPE HATCHES

FUTURE OF NAVIGATION -2

4. NAV-COMM SERVICES:

- FEE FOR SERVICE
- AIRCRAFT AND SHIPS
- TRUCK FLEETS, DISPATCH
- UNDEVELOPED COUNTRIES AVOID WIRED FACILITIES
- MEO AND GEO MIX
- WILL REQUIRE PRECISE INERTIAL NAVIGATION

5. INERTIAL:

- LESS CIVIL ACCURACY DUE TO 100% GPS COVERAGE
- MILITARY USE OF PRECISE INERTIAL
- GPS-INERTIAL FOR CATEGORY ii AND iii LANDING
- RANGE OF COST AND ACCURACY

6. WORLD-WIDE DIGITAL DATA BASES:

- GOVERNMENT AND PRIVATE DATA BASES
- TERRAIN HEIGHT AND SEA FLOOR
- STREET MAPS OF LARGE CITIES
- INTERCITY MAIN ROUTES
- HARBORS AND COASTLINES
- AERONAUTICAL VISUAL:
  - AIRPORTS, RADIO AIDS, TERRAIN HEIGHTS
- AERONAUTICAL INSTRUMENT:
  - AIRWAYS, MEA, APPROACH PLATES

FUTURE OF NAVIGATION -3

7. AUTOMOTIVE NAV AND ROUTE OPTIMIZATION:

- CELLULAR AND MICROCELL RANGING
- ON-BOARD GPS
- AREA MAPS, RADIOED CONGESTION IN CITY
- EMERGENCY FLEET
- DELIVERY FLEETS
- RENTAL CARS
- COMMUTER VANS
- LUXURY CARS

8. SPACECRAFT:

- WORLD-WIDE TDRS COVERAGE BELOW 4000 NM: UPLINKED FIXES
- GPS COVERAGE IN LOW ORBIT: ON-BOARD FIXES
- LASER GYROS ON BOARD
- SPACE STATION AUTONOMY, LANDMARKS
  - LUNAR BASE: LAUNCH SLED, ROVERS, BACK-SIDE OBSERVATORY
  - MARS: AUTONOMOUS SURFACE NAVIGATION

9. MILITARY NAVIGATION:

- GPS GLOBAL FOR SHIPS, AIRCRAFT, ARMY, BOOSTERS
- JTIDS, PLRS LOCAL
- GPS - SINS, BOTTOM-MAP FOR SUBMARINE
- TERRAIN-FOLLOWING AND ROUTE-PLANNING
- VHSIC CIRCUITS, EMBEDDED COMPUTERS WIDESPREAD
- RADIATION HARDNESS

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