WAAS navigation: IFR operations review

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Agenda

- WAAS overview
- Pre-WAAS IFR navigation
- Post-WAAS IFR navigation
- Approach design principles
- WAAS equipment
- Charting and procedures
- Regulations

Glossary

- TSO
  - Technical Standard Order
- Accuracy
  - True versus claimed navigation fix
- Integrity
  - Ability of system to protect user from inaccurate fix
- RAIM
  - Receiver Autonomous Integrity Monitoring
- FDE
  - Fault Detection and Exclusion
- RNP
  - Required Navigation Performance

•Accuracy is the difference between the corrected navigation fix and the true position.

- •Accuracy or more specifically, Navigation Sensor Error (NSE) is defined as the difference between the position estimated by the navigation sensor and the true position of the aircraft which is only exceeded 5% of the time in the absence of system failures.

•Integrity measures the ability of the system to protect the user from inaccurate position estimates in a timely fashion.

•Continuity measures the navigation system's ability to complete an operation without raising an alarm.

•Availability is computed as the fraction of time the WAAS system is providing position fixes to the specified level of accuracy, integrity and continuity.

WAAS purpose

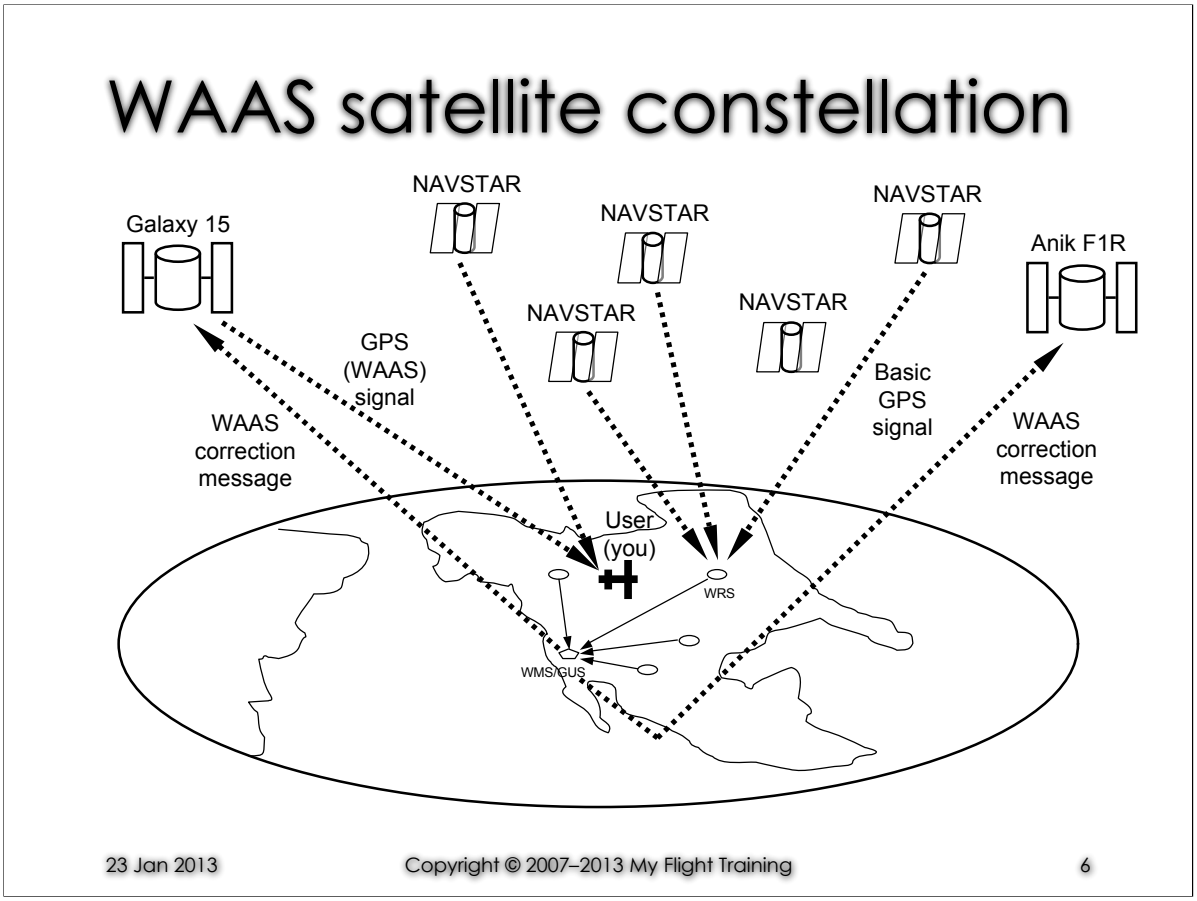
- Wide Area Augmentation System
  - Commissioned July 2003
- WAAS compensates for inherent un-augmented (basic) GPS errors:
  - Selective Availability (SA)
    - Shutdown by presidential order May 2000
  - Satellite ephemeris (orbit) errors
  - Satellite atomic clock drift
  - Ionospheric signal propagation delays

WAAS components

- Wide area reference station (WRS)
  - Precisely surveyed antenna/station
  - GPS receiver
  - Error computation (differential GPS)
- Wide area master station (WMS)
  - Integrates error data from multiple WRSs
- Ground uplink station (GUS)
- Geosynchronous satellites (Intelsat, PanAmSat)
- WAAS downlink message
  - Compatible with original GPS signal
  - Appears to be an additional GPS satellite

•WAAS dowlink messages

- •Fast
  - •Relative to position of user (receiver)
  - •Different receivers see different effects/satellites
  - •Ionospheric map
- •Slow
  - •Global to all users
  - •Ephemeris
  - •Clock drift



•NAVSTAR is the original (Block I) GPS implementation. Block IIIC is the latest.

- •24 required to meet design performance
- •31 actually operational in orbit

•Later improved Blocks were launched under a variety of satellite names.

•WAAS is available only in North America by virtue of WRS distribution and geostationary satellite coverage.

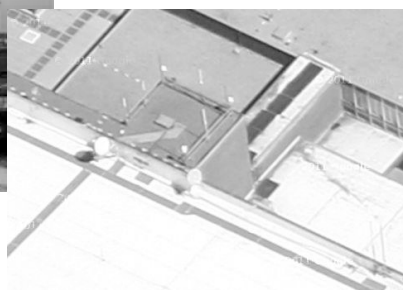
•Other parts of the world are implementing their own GNSS and differential correction constellations.

•The WAAS receiver picks up both basic GPS signals from the GPS satellites and WAAS correction messages from the geosynchronous satellites.

- •There is a west and an east geosynchronous satellite.

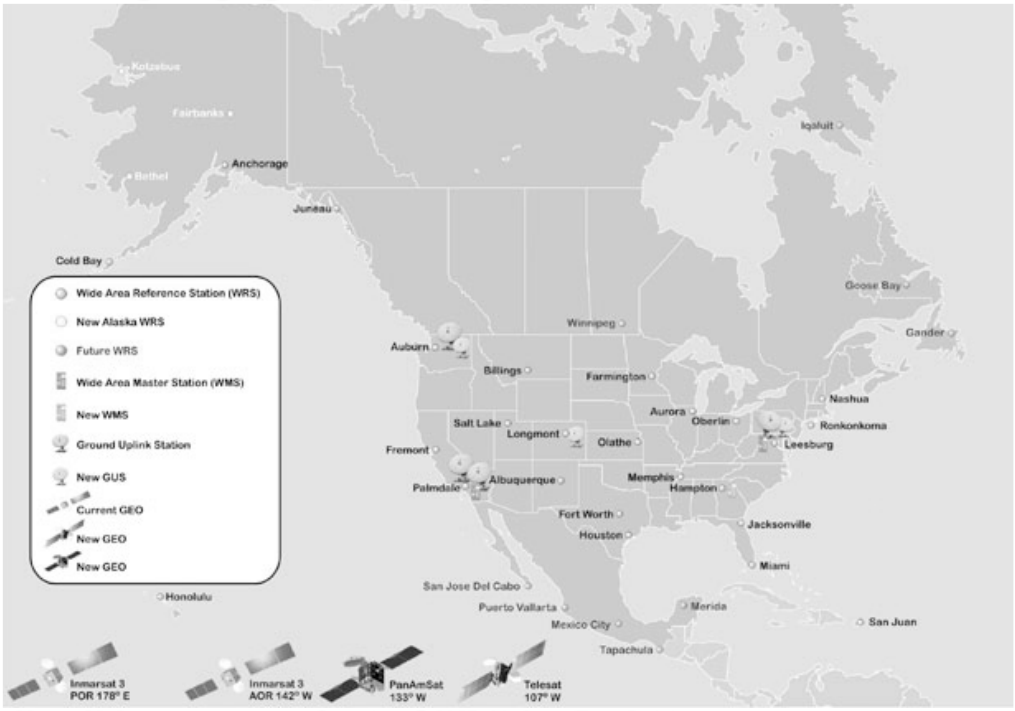
WAAS reference stations

Barrow, Alaska (PABR)



Oakland ARTCC (KZOA)

WRS locations



The distribution of WRSs makes it clear why WAAS service is available only in North America.

WAAS versus basic GPS

- Improved and more useable accuracy
  - Horizontal (LNAV)
  - Vertical (VNAV)
- Improved availability
  - Decreased susceptibility to satellite outage
- Improved integrity
  - More immediate fault detection
  - Specified maximum alarm delay
  - Measurable quality of service
  - Real-time satellite monitoring and exclusion

•Horizontal Alarm Limit (HAL)

•Vertical Alarm Limit (VAL)

WAAS performance claims

- Accuracy
  - Horizontal Accuracy < 1.5 meters
    - (basic GPS: 15 meters)
  - Vertical Accuracy < 3 meters
    - (basic GPS: unusable for navigation)
- Availability
  - > 99.99%
    - (within continental U.S. with all system components operating)
    - Intelsat failed from April 2010 through January 2011 degrading Alaska WAAS

Certification standards

- Certification
  - TSO C-129
    - Basic GPS
    - Baro-VNAV aided GPS
  - TSO C-145
  - TSO C-146
    - WAAS (C-146 through C-146c)
    - LP approaches added in C-146b
- Integrity system
  - GPS: RAIM algorithm
  - WAAS: WMS, downlink messages, receiver algorithms

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•TSO is Technical Standard Order

•TSO C-129 covered approach-certified aviation GPS beginning in the 1990s

- •Examples
  - •Garmin GNS430, GNS530
  - •UPS AT (Garmin) GX60
  - •Bendix/King KLN89B, KLN90B, KLN94
  - •Trimble 2000 Approach

•TSO C-145 is FMS with WAAS

•TSO C-146a

- •Examples
  - •Garmin GTN750, GTN650, GNS430W, GNS530W, GNS480
  - •Garmin G1000 (with WAAS hardware and software)
  - •UPS AT (Garmin) CNX80

•TSO C-146b

•TSO C-146c (current)

Navigation system approval

- Basic GPS certified as "supplemental" navigation
  - VOR receiver must be installed and operational
  - VOR ground stations must be operational along route of flight
  - En route RAIM failure requires VOR fall-back
- WAAS certified as "sole-means" navigation
  - VOR need not exist, be operational, or be monitored along planned route

Basic-GPS integrity

- RAIM
  - Receiver Autonomous Integrity Monitoring
  - Over-determined navigation solution
  - Four satellites required for 3D navigation solution (intersecting spheres)
  - RAIM requires at least five satellites or four satellites plus barometric source (baro-aiding)
  - May be limited by satellite geometry or terrain (insufficient satellites in view)
  - GPS approach cannot be initiated if *approach-level* RAIM (APR) unavailable

•GPS satellites, contrary to popular belief, are not in geosynchronous orbits. They are in 12-hour orbits so a given satellite appears to rise and set.

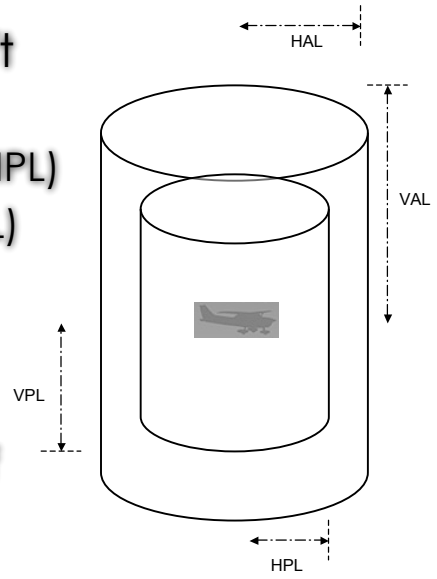
•The operational GPS constellation of 24 satellites is designed so that the minimum number of satellites to compute a position is in view everywhere on earth.

•RAIM is always operating. Its level of accuracy changes depending on the phase of flight and the immediate level of accuracy is displayed by the GPS navigator (e.g., TERM).

•The levels of RAIM accuracy are OCN, ENR, TERM, and APR.

WAAS integrity

- Receiver computes aircraft position confidence limits:
  - Horizontal Protection Limit (HPL)
  - Vertical Protection Limit (VPL)
- Nominates best approach level for which HPL, VPL better than "alarm limit"
- Fall back to LNAV (RAIM) if no WAAS or alarm limit exceeded



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Ionospheric propagation delay is the largest single contributor to basic GPS inaccuracy.

IFR alternate planning

- WAAS removes constraint to plan non-GPS approach at a required alternate
- Selected GPS or RNAV approaches now qualify for alternate minimums
  - Ⓐ NA removed
- Planning must assume GPS or RNAV approach flown using LNAV-only minimums
- Alternate selection should be based on each approach, *not* the entire airport
- As always, if alternate approach is flown, charted, not alternate, minimums apply

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•GPS alternate planning required assumption that GPS is unavailable at the alternate.

- •GPS approach cannot be planned at alternate
- •GPS substitution for DME or ADF on a conventional approach cannot be planned at alternate
- •All GPS approaches were marked “not authorized” (NA) for alternate minimums.
  - •On NACO plates, NA legend is in the notes block
  - •On Jeppesen plates, alternate minimums are tabulated at the bottom of the airport page.

•WAAS alternate planning should examine each approach at the planned alternate, not the airport as a whole.

- •Some GPS and RNAV (GPS) approaches now have the NA legend removed, and they are available as alternate candidates.
- •The reverse-A legend may still appear. It means alternate minimums for this approach are non-standard. Check the appropriate section of the TPP.
- •For Jeppesen, check the alternate minimums tabulation. Under WAAS, GPS and RNAV (GPS) approaches may be listed there.
- •For planning purposes, the approach must assume lateral navigation (LNAV) minimums only. Vertical navigation must be assumed to be out--of-tolerance.
  - •This means that RNAV (GPS) approaches with LPV minimums only cannot be considered.

•As always, minimums consideration is for planning prior to departure only. Upon proceeding to any alternate and flying an approach, the actual published minimums, including vertical navigation minimums, apply.

NOTAM system

- GPS
  - Global to all users
    - `!GPS 01/003 GPS PRN 5 OTS WEF 0701111200-0701120001`
- WAAS
  - Area-wide (ARTCC) or airport-specific
  - W chart note denotes WAAS vertical outages may occur daily *without* NOTAM
  - UNREL (unreliable) or UNAVBL (unavailable)
    - `!SFO 12/051 SFO WAAS LNAV/VNAV AND LPV MNM UNREL WEF 0512182025-0512182049`
    - `!ZDC 12/052 ZDC WAAS LPV AND LNAV/VNAV MNS UNAVBL 341100N/1245600W WEF 05061011500`

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•WAAS and GPS outages are reported by NOTAM.

•GPS outages are reported for location identifier GPS.

•GPS satellite outages are reported by PRN, or “pseudo-random number,” which effectively is the number of the satellite.

•WAAS NOTAMs are issued

•by specific location identifier for large terminals.

•by ARTCC location identifier for wide areas and for terminals not covered by specific NOTAMs.

•Oakland Center location identifier is ZOA

•On NACO charts, reverse-W symbol in notes block denotes that site-specific NOTAMs for this airport are not issued

VOR equipment check

- 14 CFR 91.171
  - "No person may operate a civil aircraft under IFR using the VOR system of radio navigation unless the VOR equipment of that aircraft…has been operationally checked within the preceding 30 days"
- If you navigate exclusively with WAAS RNAV and file */G*
  - "VOR system of radio navigation" is not used or required
  - VOR system check not required

ICAO approach classification

- Non-precision
  - No vertical guidance
- Precision
  - Glidepath deviation
  - ILS, MLS, PAR, GLS
- Approach with Vertical Guidance (APV)
  - Glidepath deviation
    "not meeting precision standards of ICAO Annex 10"
  - LNAV/VNAV, LPV, LDA/GS
  - Instrument presentation same as "precision"
  - Qualifies as "precision" per Jan. 2010 IFR PTS

- APV is classified as a new kind of vertical guidance instrument approach
  - Technically not considered a "precision" approach
    - Not meeting ICAO Annex 10 standards
  - From pilot perspective, flown identically to precision approach with same navigation presentation and flown to a DA(H), not MDA
- Instrument Rating practical test standard (PTS) published January 2010
  - APV approaches qualify as meeting the requirement to perform a "precision" approach
  - Applicable to instrument rating practical test
  - Applicable to instrument proficiency check (IPC)
- AIM 5-4-5(a)(7)

  (a) Precision Approach (PA). An instrument approach based on a navigation system that provides course and glidepath deviation information meeting the precision standards of ICAO Annex 10. For example, PAR, ILS, and GLS are precision approaches.

  (b) Approach with Vertical Guidance (APV). An instrument approach based on a navigation system that is not required to meet the precision approach standards of ICAO Annex 10 but provides course and glidepath deviation information. For example, Baro-VNAV, LDA with glidepath, LNAV/VNAV and LPV are APV approaches.

  (c) Nonprecision Approach (NPA). An instrument approach based on a navigation system which provides course deviation information, but no glidepath deviation information. For example, VOR, NDB and LNAV. As noted in subparagraph h, Vertical Descent Angle (VDA) on Nonprecision Approaches, some approach procedures may provide a Vertical Descent Angle as an aid in flying a stabilized approach, without requiring its use in order to fly the procedure. This does not make the approach an APV procedure, since it must still be flown to an MDA and has not been evaluated with a glidepath.

RNAV approach minimums

- LNAV
  - With or without advisory vertical guidance
  - Flown via stepdowns to *MDA; or,*
  - Flown via computed glidepath to *MDA*
- LP
  - LPV horizontal, no vertical guidance to *MDA*
- LNAV/VNAV
  - Designed for non-WAAS (baro-VNAV)
  - Flown via computed glidepath to *DA(H)*
- LPV
  - Designed for WAAS only
  - Flown via computed glidepath to *DA(H)*

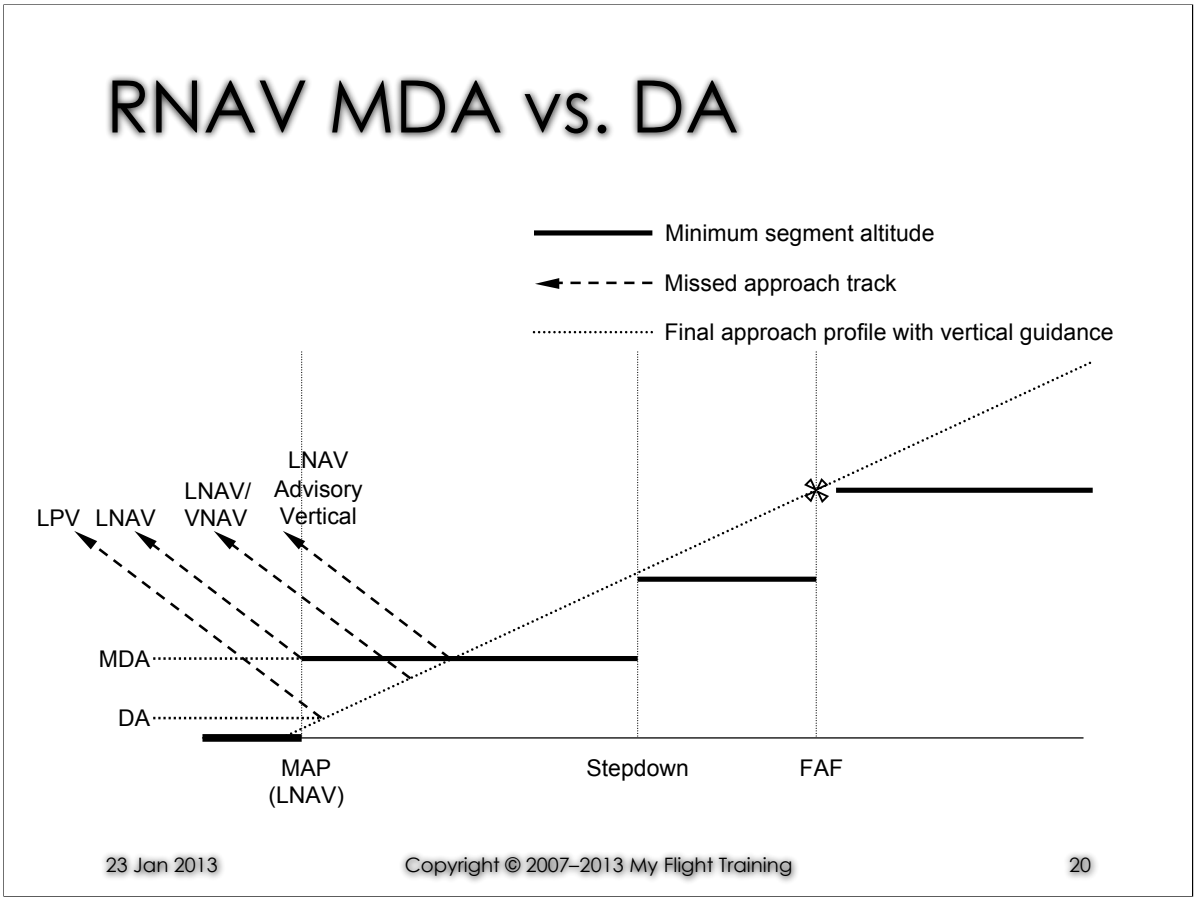
•These are the charted minimum lines titles

•LP was added later

- •It may not be supported by the software in some earlier WAAS receivers
- •It offers LPV horizontal accuracy, but does not provide vertical guidance
- •Usually due to surrounding terrain
- •Same relationship between LPV/LP as ILS/LOC

•LPV normally offers 250 HAT DH

•LPV-200 offers 200 HAT DH



- Vertical guidance approaches flown to DA(H)
  - They may not be “precision” approaches despite having vertical guidance
- Non-vertical guidance approaches flown to MDA

Why no LPV at PAO, SQL?

- Qualification for VNAV minimums:
  - TERPS obstacle assessment
  - Runway length
  - Runway marking
  - Approach lighting system
- Some runway ends that don't qualify for LPV can get LP
  - Due to obstacles
- LPV or LNAV/VNAV minimums *can be worse* than LNAV!
  - VCB RNAV Y RWY 20, VCB RNAV Z RWY 20
  - Because of missed approach path obstacles

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•Required Obstacle Clearance (ROC)

- •Is a sloping surface for vertical guidance approaches
- •Is a flat surface between fixes for "dive-and-drive" approaches

•Differing Obstacle Clearance Surface (OCS) shapes sweep up different obstacles, resulting in different MDA or DA

- •Guideslope Qualification Surface (GQS) governs vertically-guided approaches
- •Close-in obstacles may penalize a vertical guidance approach (GQS) where an approach with an MDA would not be affected
- •See TERPS for details

WAAS minimum availability

- At approach enable (FAF active), WAAS navigator notifies pilot of lowest minimums, per
  1. authorized by approach (database); and,
  2. equipment capability; and,
  3. immediate geometry or integrity limitation by comparison of HAL/VAL to HPL/VPL
- Navigator minimums are fixed for duration of that approach
  - Pilot *cannot* select minimums for given approach
- Pilot can elect to fly to any minimums equal to or less favorable than navigator annunciation
  - Fall-back to LNAV minimums if WAAS failure

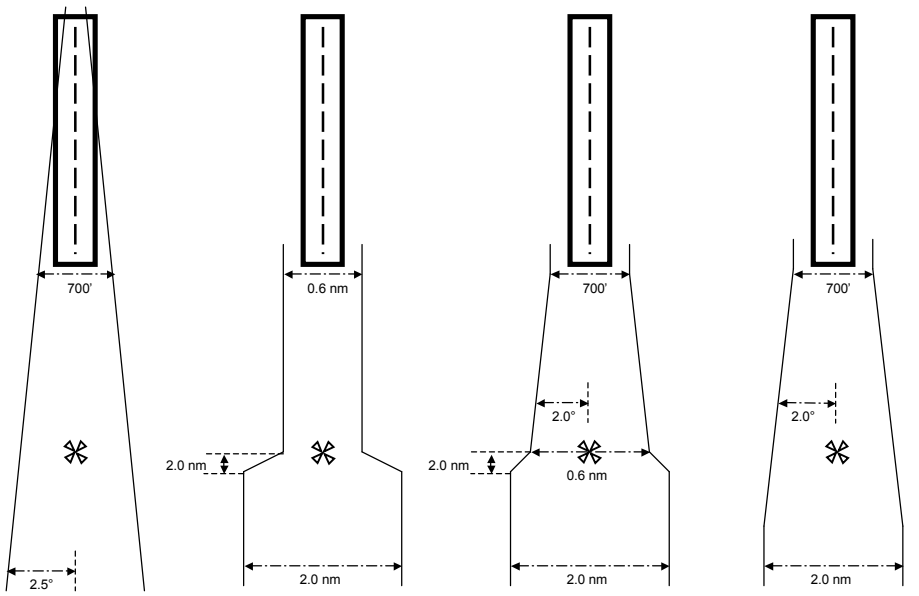
Final approach scaling

- ILS/LOC
  - Angular localizer signal
    - 3° to 6° (5° nominally)
  - 700 ft wide final approach course (full-scale deflection) at runway threshold
- GPS
  - Final approach course width ramps from 1.0 nm to 0.3 nm, 2.0 nm outside of FAF
    - Per TSO C-129
  - Rectangular 0.3 nm width from FAF to MAP

Final approach scaling

- WAAS/LPV
  - Angular final approach course width simulating localizer
    - More sensitive as threshold approached
    - Approximates localizer sensitivity at threshold
  - Course width outside FAF fans out to match 1.0 nm terminal area sensitivity
  - Course sensitivity outside FAF is dependent on approach IAF selection by pilot:
    - Pilot navigation via IAF and IF; versus,
    - Vectors to final

Final approach scaling



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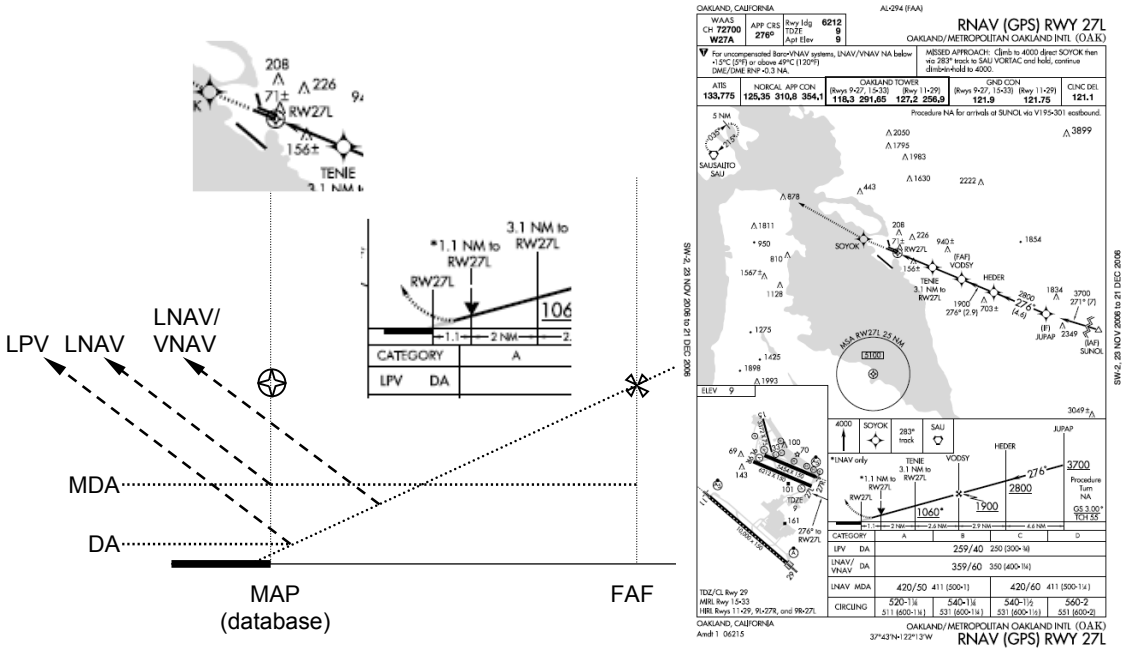
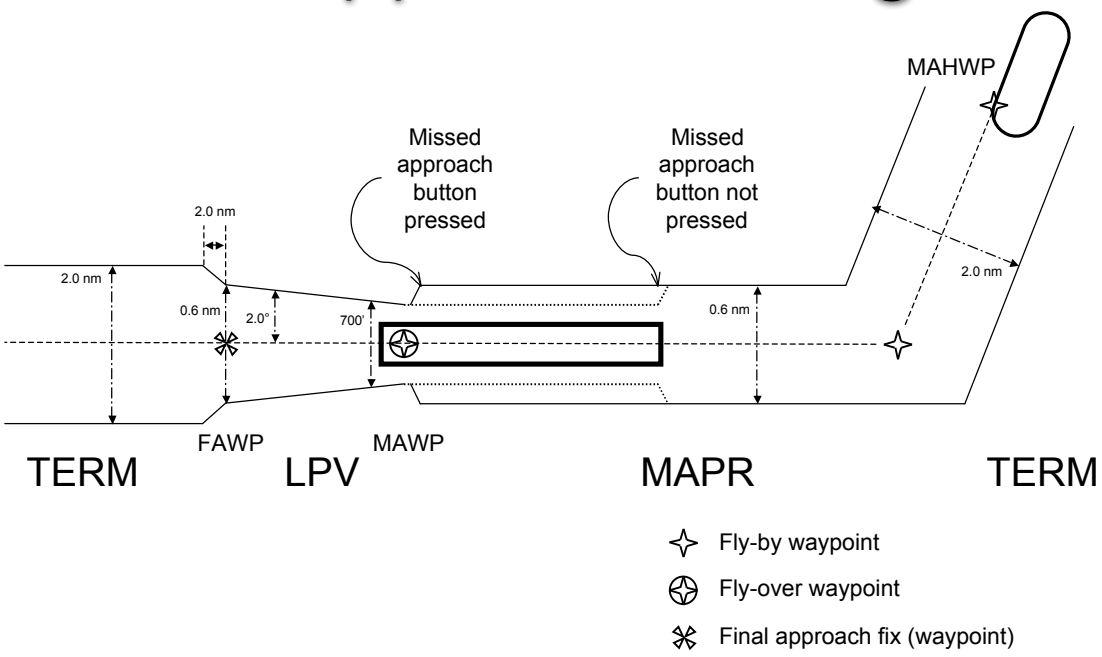
- Splay computations
  - 2.0°
    - 350’ at threshold (10022 ft) from origin
    - 0.3 nm at 6.94 nm (42140 ft) from threshold
    - 1.0 nm at 27 nm (163856 ft) from threshold
  - 2.5°
    - 350’ at threshold
    - 0.3 nm at 5.55 nm (33732 ft) from treshold
    - 1.0 nm at 22 nm (131055 ft) from threshold

Where is the MAP?



- On the glideslope at barometric minimum for precision/APV
  - LNAV/VNAV
  - LPV
- At the published (database) MAP for LNAV
- What about the chart?
  - NACO
    - NACO charts show transition from solid to dashed procedure track at lowest precision minimum
    - FAF-to-MAP table not included for RNAV approach
    - Plan view shows miniaturized fly-over waypoint symbol for LNAV MAP
    - Profile view show LNAV MAP
    - Study and know Aeronautical Chart User's Guide!
    - There are many different ways that the MAP can be depicted, depending on the type of approach. On all approach charts it is depicted in the profile and planviews by the end of the solid course line and the beginning of the dotted missed approach course line for the top-line/lowest published minima. For a precision approach, the MAP is the point at which the aircraft reaches the DA or DH while on the glide slope. On some nonprecision approaches,the MAP is given as a fixed distance with an associated time from the FAF to the MAP based on the groundspeed of the aircraft. A table on the lower right hand side of the approach chart shows the distance in NM from the FAF to the MAP and the time it takes at specific groundspeeds, given in 30- knot increments.
  - Jeppesen charts are clearer
    - Show missed approach track profile for each minimum
- Don't fly to database MAP on a VNAV profile!

Missed approach scaling



- TERM to IF or when FAWP becomes active
- LPV after IF or FAWP active
- MAPR at MAWP with straight-ahead missed
- TERM at first turning fix after MAWP

WAAS approach charting

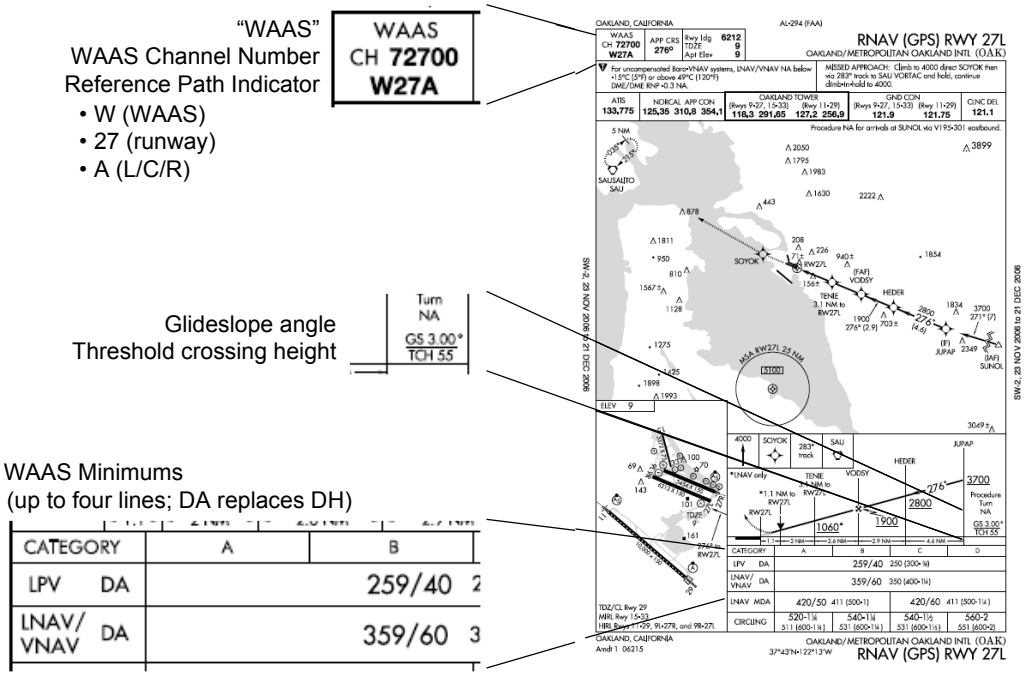
- RNAV (GPS) approach title
  - Replaces GPS-only design
    - Most "GPS" approaches have been replaced by "RNAV (GPS)"
      - 2004 (SQL)
      - 2013 (E16)
      - unknown (PAO)
  - Allows use of non-GPS FMS (DME/DME, IRU)
    - May be noted "DME/DME RNP 0.3 NA"
    - May be noted "baro VNAV NA" below some minimum temperature
    - DME/DME FMS notes can be ignored by GPS users

Non-overlay GPS and RNAV (LNAV) approaches are designed to the same criteria.

WAAS approach charting

- Multiple straight-in approaches using *same final approach guidance* may be charted to a given runway
  - Distinguishing alphabetic suffix assigned:
    - Z, Y, X, etc.
  - May differ in final approach track, minimums, missed approach gradient
  - Pilot's approach briefing is critical:
    - Ensure chart, database selection, and approach clearance are in sync
    - Ensure able to accept approach
      - Minimums annunciated
      - Missed approach climb gradient achievable

WAAS approach charting



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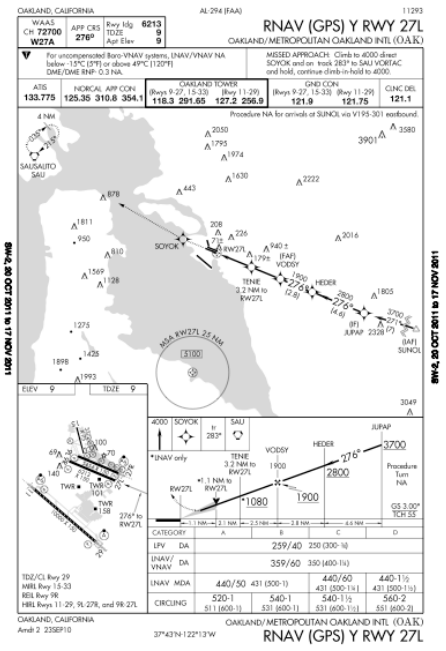
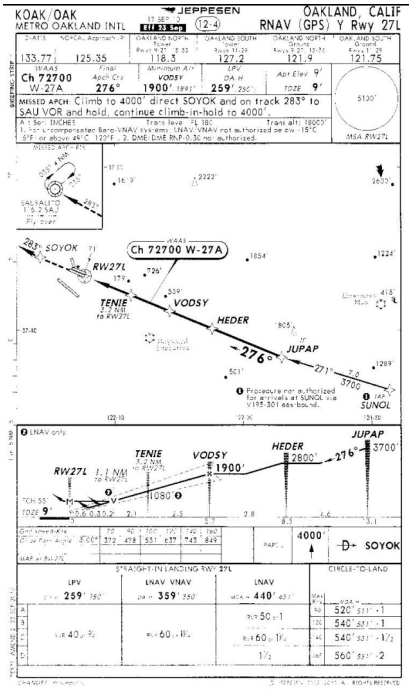
- WAAS data block
  - "WAAS"
  - Channel number (five digits)
  - Reference Path Indicator
    - W
    - Runway numeric designator
    - A, B, C, etc. per ICAO standards surroages for L, C, R
- WAAS minimums
  - Up to four lines
    - LPV
    - LNAV/VNAV
    - LNAV
    - Circling
  - GLS or GLS-PA lines have been removed

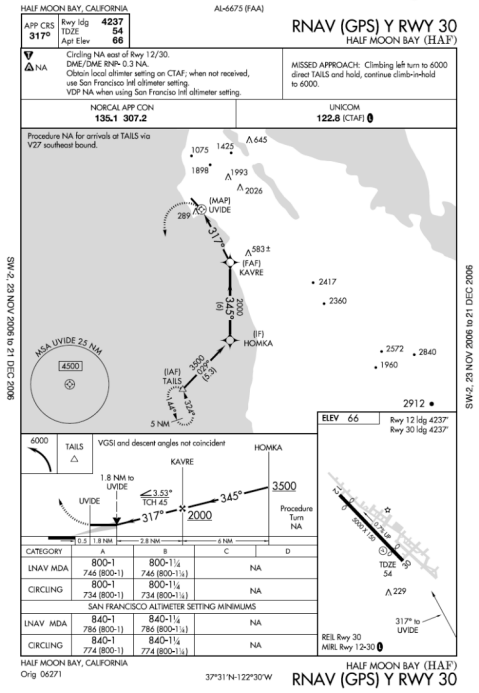
Jeppesen vs. Aeronav

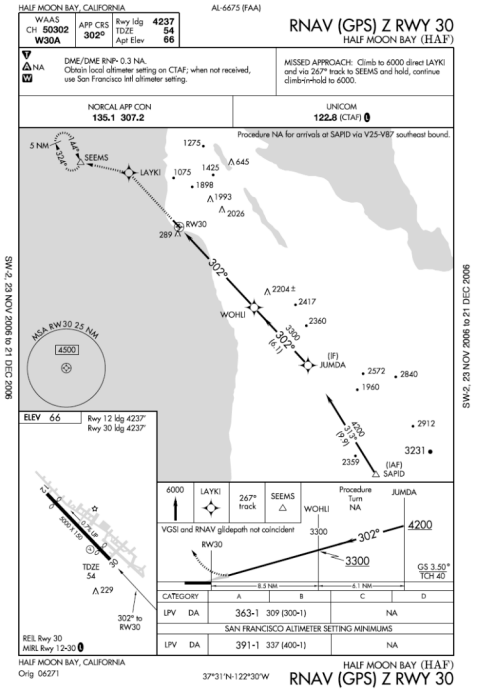




- Minimums layout
- Timing table (Jeppesen only)
  - Vertical descent angle
  - Rate of descent tabulation
- Missed approach symbols
  - Jeppesen
    - M for LNAV MAP
    - Upward-turning arrows for each APV missed
  - Aeronav
    - LNAV MAP marked with undistinguished fix (usually at threshold)
    - Lowest minimums MAP transitions to dotted line in profile view

HAF RNAV (GPS) RWY 30





- Different final approach tracks
- Separate minimums
- LPV chart has no circling minimums
- LPV approach has straight-ahead missed (MAPR)

HWD RNAV Y/Z RWY 28L

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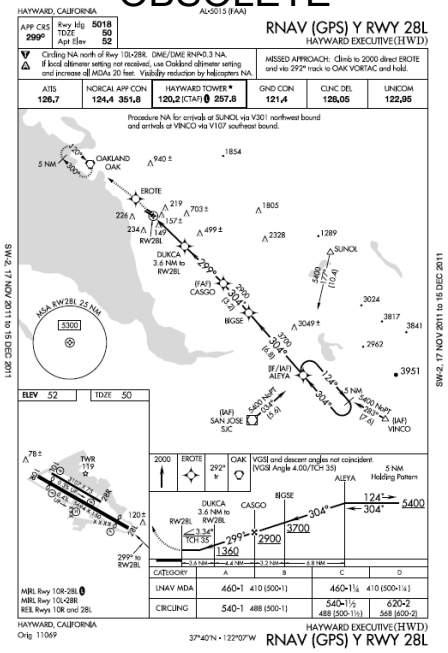

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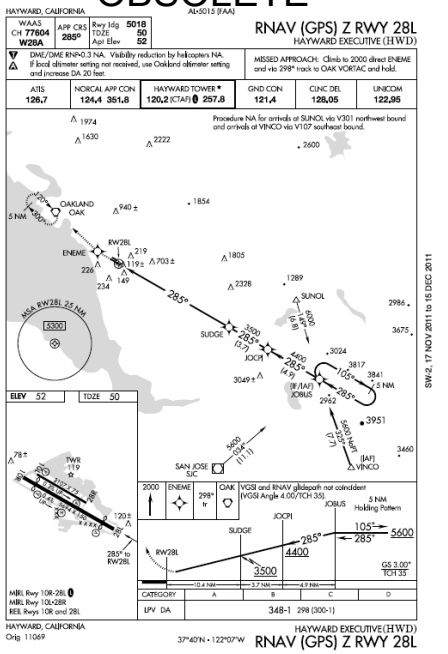
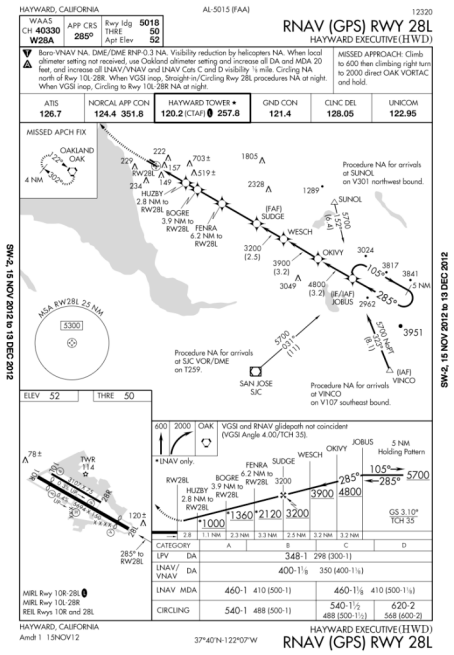


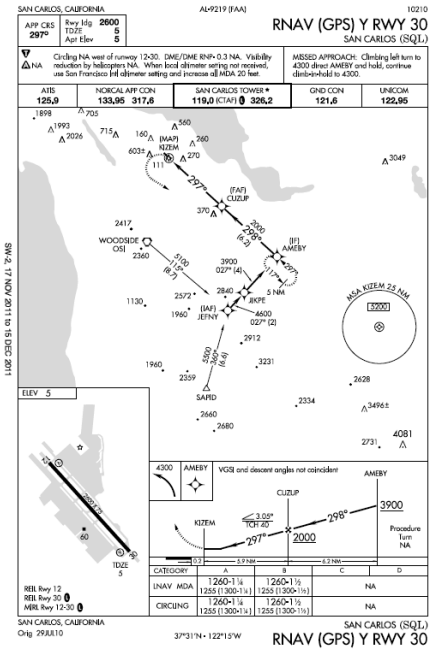
- Different final approach tracks
- LPV aligned with runway heading
- LPV chart has no circling minimums

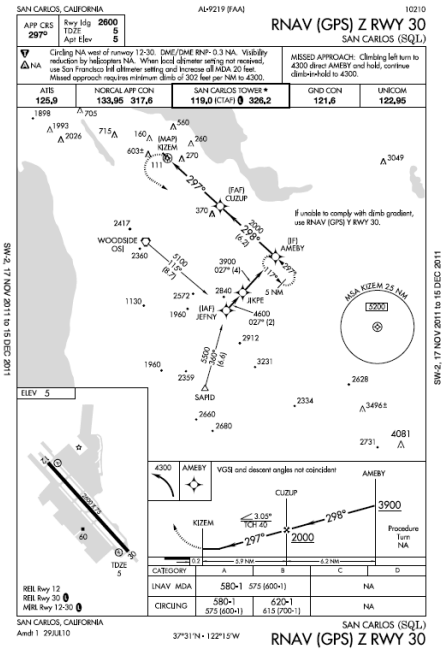
HWD RNAV (GPS) RWY 28L



- Different final approach tracks
- LPV aligned with runway heading
- LPV chart has no circling minimums

SQL RNAV (GPS) RWY 30





- Identical final approach tracks
- Identical approach fixes
- Identical minimums labels
- Approaches differ only in non-standard missed-approach climb gradient, which necessitates different MDAs

Is my GPS WAAS-capable?

- Garmin
  - G1000, G950, etc. (requires GIA63W option)
  - GPS400W, GNC420W, GNS430W
  - GPS500W, GNS530W
  - GTN625, GTN635, GTN650, GTN725, GTN750
  - CNX80, GNS480
- Avidyne
  - IFD510, IFD540
  - Release 9
- Check startup screen and config pages

On some equipment, WAAS is an option, and presence cannot be detected by equipment model number

•Check startup screen

•Check satellite status pages

•Check config pages

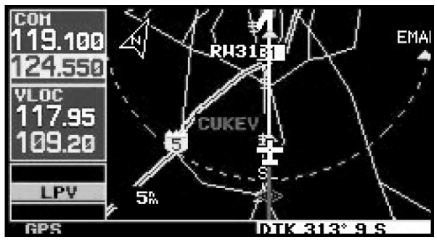
- •SBAS turned ON/OFF
- •MSAS turned ON/OFF

•RNAV approaches available for selection

- •Approaches in database but not available due to equipment are showed grayed out

Garmin WAAS commonality

- "Flight phase" annunciations (GNS 430W shown)
  - LPV



  - L/VNAV
  - LNAV+V (advisory)
  - LNAV (replaces APR)
  - MAPR

Approach level annunciations have changed

•APR is gone

•Level of WAAS horizontal/vertical accuracy is now annunciated as

- •LNAV
- •LNAV+V (LNAV with advisory vertical guidance)
- •L/VNAV
- •LP
- •LPV

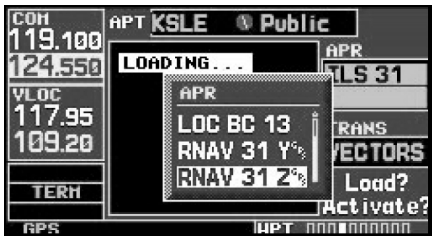
•LNAV is annunciated for conventional navaid (e.g., LOC) approaches

•MAPR is for missed approach guidance on straight-ahead misses (like LPV)

Garmin WAAS commonality

- Approach selection (GNS 430W shown)
  - By approach title

RNAV (GPS) Z RWY 31
SALEM/ MCNARY FIELD (SLE)



  - By WAAS channel ID

SALEM, OREGON

WAAS Chan **86202** W31A	APP CRS **312°**	Rwy ldg TDZE Apt Elev	**5811** **214** **214**

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What else?

- A safe IFR pilot in the new RNAV world knows:
  - Much more on charting
    - Terminal area arrivals (TAAs)
    - Jeppesen charts
  - Waypoints types, flight plan legs, autopilots
  - RNAV and RNP levels
  - RNAV arrivals and departures
    - ODPs, SIDs, STARs
  - Subtle non-WAAS vs. WAAS navigator gotchas
  - Next steps:
    - Consult a CFI
    - Find a WAAS-equipped airplane
    - Fly!

Reference material

- Aeronautical Chart User's Guide
- AIM
  - 1-1-19 GPS
  - 1-1-20 WAAS
  - 1-1-21 LAAS and GLS
  - 1-2-1 RNAV
  - 1-2-2 RNP
  - 1-2-3 DME and ADF substitution
  - 5-4-5 instrument approach charts
- AC
  - 90-94 IFR use of GPS
  - 90-100A Terminal and En Route RNAV Operations
  - 150-5300 Airport Qualification
- Orders
  - 8260.54A RNAV approach design