Feasibility of Increasing Loran Data Capacity using a Modulated Tenth Pulse

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Background

- In Dec 06 at eLoran description meeting at NAVCEN, question raised: Is there room between adjacent signals for even the current modulated 9th pulse? (violation of Signal Spec.)
- In Jan 07, Sherman Lo & I were asked to prepare brief for the FAA's GNSS Evolutionary Architecture Study (GEAS) on whether the LDC could provide some subset of the WAAS message mainly for integrity.
  - We concluded it could &
  - proposed a high frequency channel of 2 modulated pulses (a 9th and 10th) with 1 message/12 GRI as opposed to the current 24 GRI format to meet stringent time to alarm requirements.

WAAS on eLoran Summary II

- FEC provides message alignment & integrity
- Used on one rate of dual rate station
  - Other rate would support current 9th Pulse applications (NPA, Maritime Harbor Entrance & Approach, Time & Frequency)
- Message Design
  - Overhead: 6 bits for message type, 3 bits for other overhead (Issue of Data, etc.)
  - Each transmitter sends different messages (good for coverage area)
  - Max 20 satellites visible in coverage area
- More details in backup slides

WAAS on eLoran Summary I

- Broadcast on eLoran 9th and 10th pulse
  - Identical to current Loran Data Channel except 2 pulses to reduce message length 0.71 to 1.2 sec. to meet time to alarm
  - 32 state (5 bit) Pulse Position Modulation (PPM)
  - 45 bit message (120 bit, total including FEC)
  - 6 bit message ID, 39 bit message
- Proposed design provides “full” WAAS capability to dual frequency user
  - Clock, ephemeris and integrity provided
  - No iono, S/A support, & long term with velocity
  - 75-80% Bandwidth utilization
  - UDRE reduced to 3 bits

Tenth pulse issues

- How much room is there between adjacent signals within a chain for adding an additional modulated pulse or pulses
  - In North America?
  - In the remainder of the world?
- How much room between signals is necessary to add an additional modulated pulse or pulses?
- If a second modulated pulse is added, should there be two parallel 24 GRI/epoch channels/signal or one 12 GRI/epoch channel/signal?
- Main interference to Loran is Loran: CRI (Cross Rate Interference). Two approaches to CRI mitigation in modulated Loran
  - Modulate a few data only pulses & blank data they interfere with (current LDC & proposed here)
    - Enables different data from each Loran signal
  - Modulate the navigation pulses, transmit exactly the same bits within a UTC second on all signals, wipe off data based on demodulation & decoding of strongest signal & cancel CRI. (2001 full bandwidth WAAS demo & 2002 Murder Board proposal, details available)

How much room between signals is needed?

- Depends on two parameters:
  - Minimum delay between the 8th pulse & the 1st modulated pulse or between modulated pulses?
    - Currently set to 1000 usec for 9th pulse.
    - The current SSX transmitters are set to disable any Multi-Pulse Trigger (MPT) within less than approx 850 usec of a previous MPT,
    - Trailing edge of a skywave from the 8th pulse interfering with the leading edge of the modulated pulse non-issue, as leading edge has no special significance as it does with navigation pulses. Skywaves are extra signal as opposed to interference when demodulating the LDC.
  - Minimum delay on the baseline extension between the last modulated pulse & the first navigation pulse of the next signal
    - Signal spec value is 2900 usec
      - This believed to be due to mechanical relays in earlier timing equipment and no longer valid (for equipment)
    - Real limit due to long delay skywaves, details follow

From: Existing USCG Signal Specification
(Similar words in Northwest European Document)

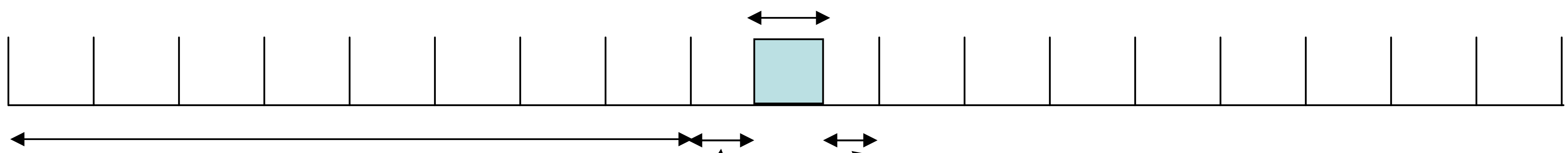
- The emission delays of secondary stations, with respect to the master, are selected to ensure that the following criteria are met within each chain wherever the signals can be received:
  - The minimum time difference between any secondary and master is 10,900 microseconds,
  - The minimum time difference between any two secondaries is 9,900 microseconds.
  - The maximum time difference is the Group Repetition Interval minus 9,900 microseconds.

Spread of Modulated Pulses

160 usec for 1

1170 usec or more for 2

2180 usec or more for 3



1^{st} to 8^{th} = 7000 usec

Min 850 usec on SSX

Currently 1000 usec

Spec: 2900 usec for Secondary??

1900 usec for Master??

Limited by late skywave

1^{st} to 1^{st}

9,900 US & Europe spec (secondary)

10,411 min in US

9,986 min in Europe

9,733 min in

Minimum TDs between Successive Signals (in us)

Europe

6731	Lessay	
	Soustons	10994
	Rugby	11101
	Sylt	12528
	Lessay	22148
7499	Sylt	
	Lessay	11038
	Vaerlandet	10714
	Sylt	42984
9007	Edje	
	Jan Mayen	10997
	Bo	10731
	Vaerlandet	9986
	Edje	46878
5930	Caribou	
	Nantucket	11002
	Cape race	10710
	Fox Harbor	10676
	Caribou	14123
5990	Williams Lake	
	Shoal Cove	11009
	George	11498
	Port Hardy	11065
	Williams Lake	16372

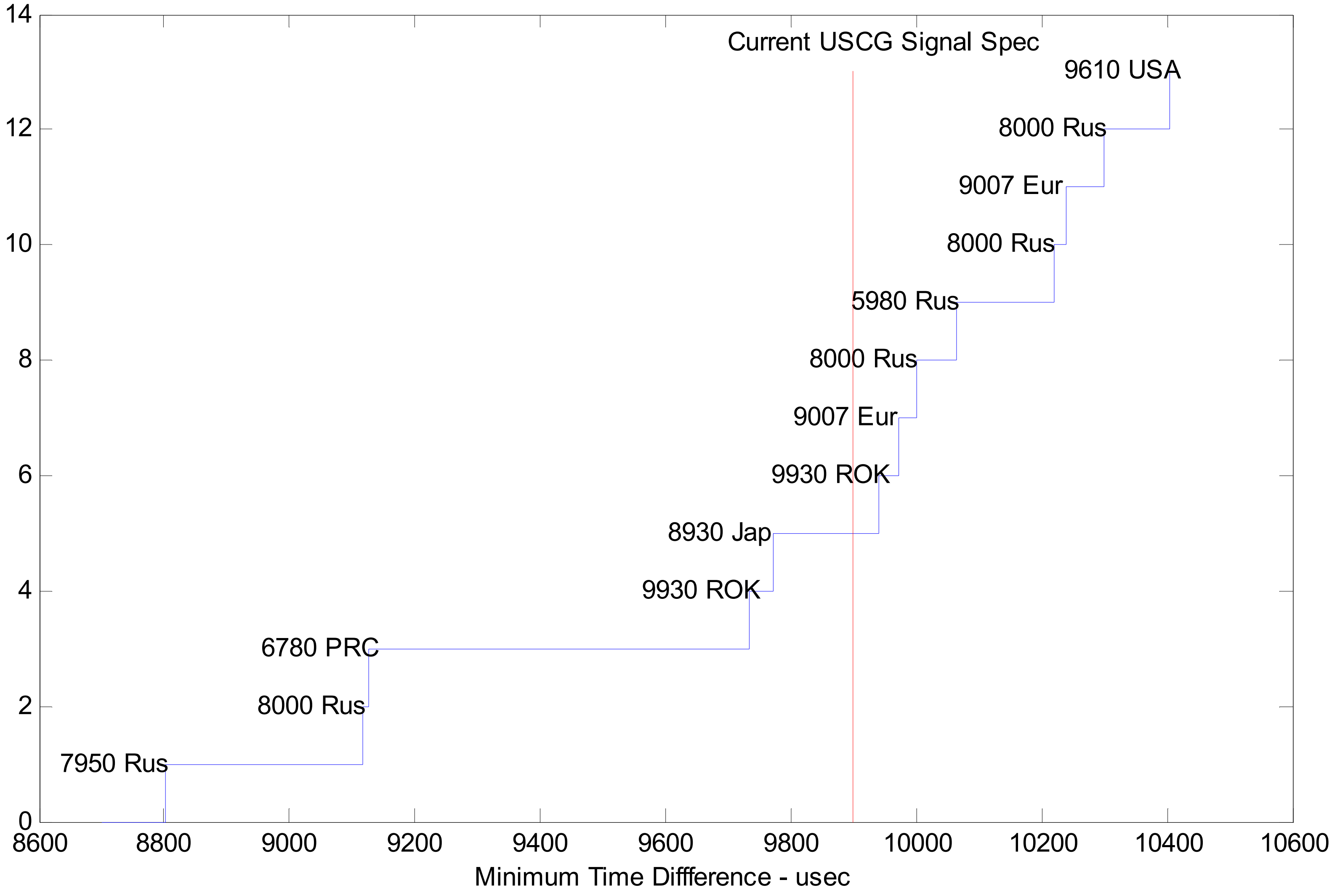
7960	Tok	
	Kodiak	10999
	Shoal Cove	11474
	Port Clarence	10943
	Tok	27739
7980	Malone	
	Grangeville	11006
	Raymondville	11876
	Jupiter	11896
	Carolina Beach	13642
	Malone	15721
8290	Havre	
	Baudette	11007
	Gillette	10992
	Williams Lake	11009
	Havre	34528
8970	Dana	
	Malone	10997
	Seneca	11812
	Baudette	11520
	Boise City	10888
	Dana	21377

9610	Boise City	
	Gillette	11000
	Searchlight	10582
	Las Cruces	10706
	Raymondville	10411
	Grangeville	10521
	Boise City	22502
9940	Fallon	
	George	11001
	Middletown	11138
	Searchlight	11262
	Fallon	55467
9960	Seneca	
	Caribou	11008
	Nantucket	11042
	Carolina Beach	11714
	Dana	11387
	Wildwood	20711
	Seneca	16600
9990	St Paul	
	Attu	10989
	Port Clarence	11304
	Kodiak	10662
	St Paul	49736

Example Calculations

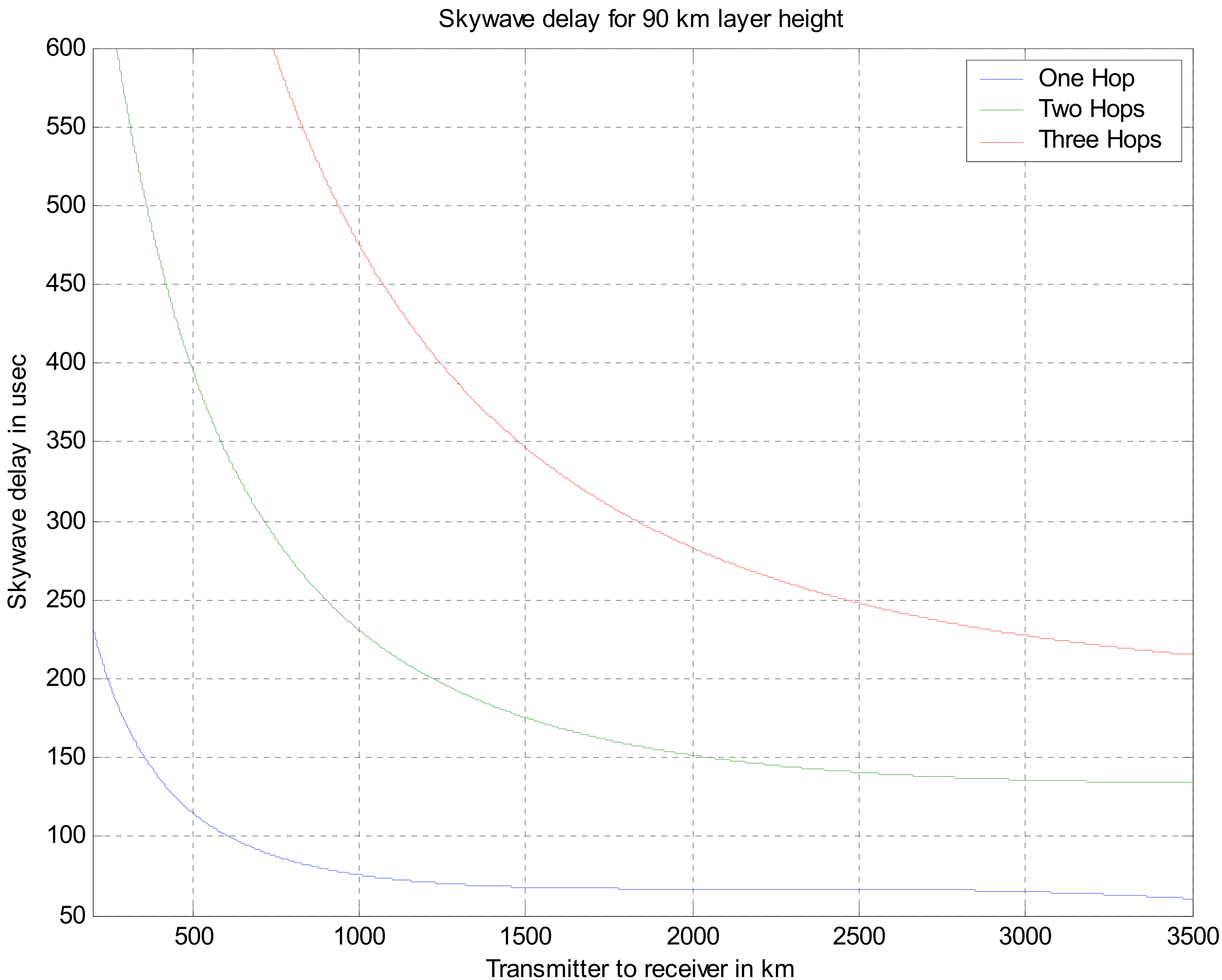
- US Examples:
  - Two modulated pulses/signal
    - If the current position of the zero symbol is left at 1000 usec, & a 10^{th} pulse added with a zero position of 2100 usec after the 8th pulse,
    - The minimum delay in North America from last modulated pulse to first pulse of next signal is 10,411-(7000 + 2100 + 160) = 1041 usec
  - Single rated stations with normal LDC channel + WAAS channel: 3 modulated pulses (one each 12 GRI/msg channel & 24 GRI/msg channel)
    - If minimum delay between pulses from same transmitter is set to 850 usec, (zero positions at 850, 1860, and 2870 usec)
    - The minimum delay on all single rated stations in North America (except Las Cruces) from last modulated pulse to first pulse of next signal is 11,000 - (7000 + 2870 + 160) = 970 usec

Minimum Time Differences on Baseline Extensions

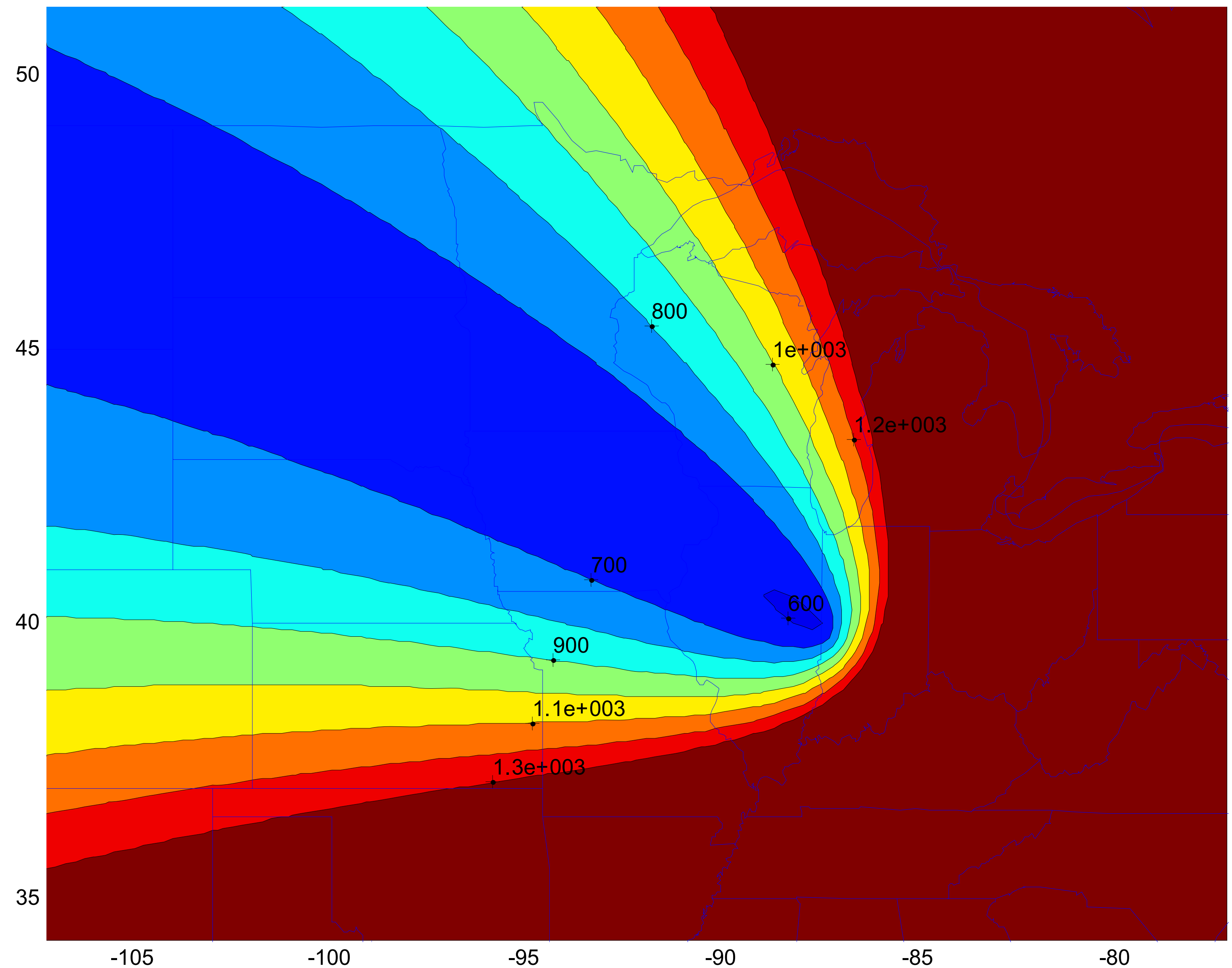


How much delay between last modulated pulse & 1st pulse of next group is needed to mitigate late skywave interference?

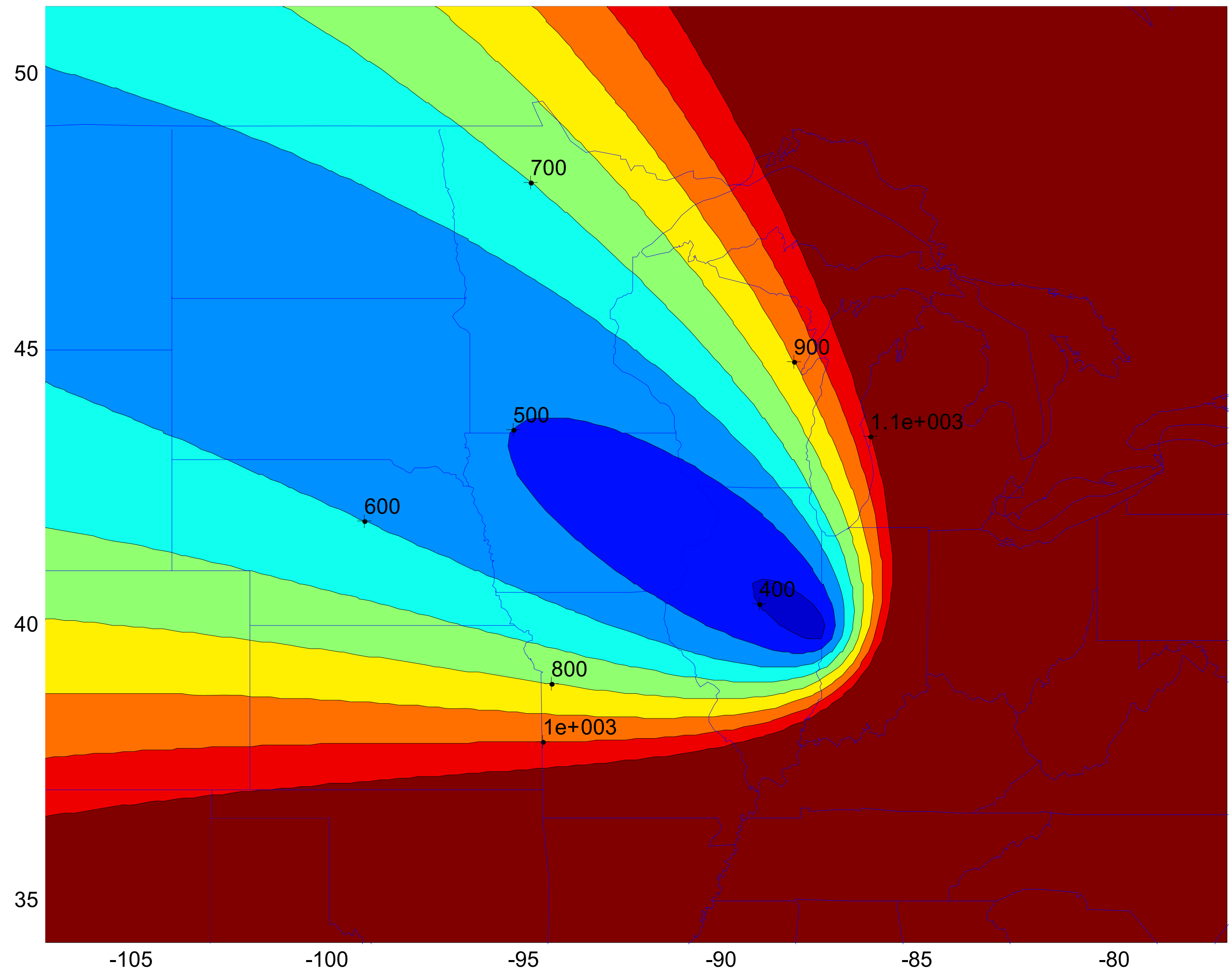
- Analysis
  - Models for groundwave and skywave amplitudes & skywave delay
  - Predict relative amplitudes of long delay skywave & groundwave
- Look at data from "*Loran-C Phase Modulation Study, Final Technical Report, Vol I (June 1970)*" by ITT


Skywave delay for 90 km layer height
One Hop
Two Hops
Three Hops
Skywave delay in usec
600
550
500
450
400
350
300
250
200
150
100
50
500
1000
1500
2000
2500
3000
3500
Transmitter to receiver in km

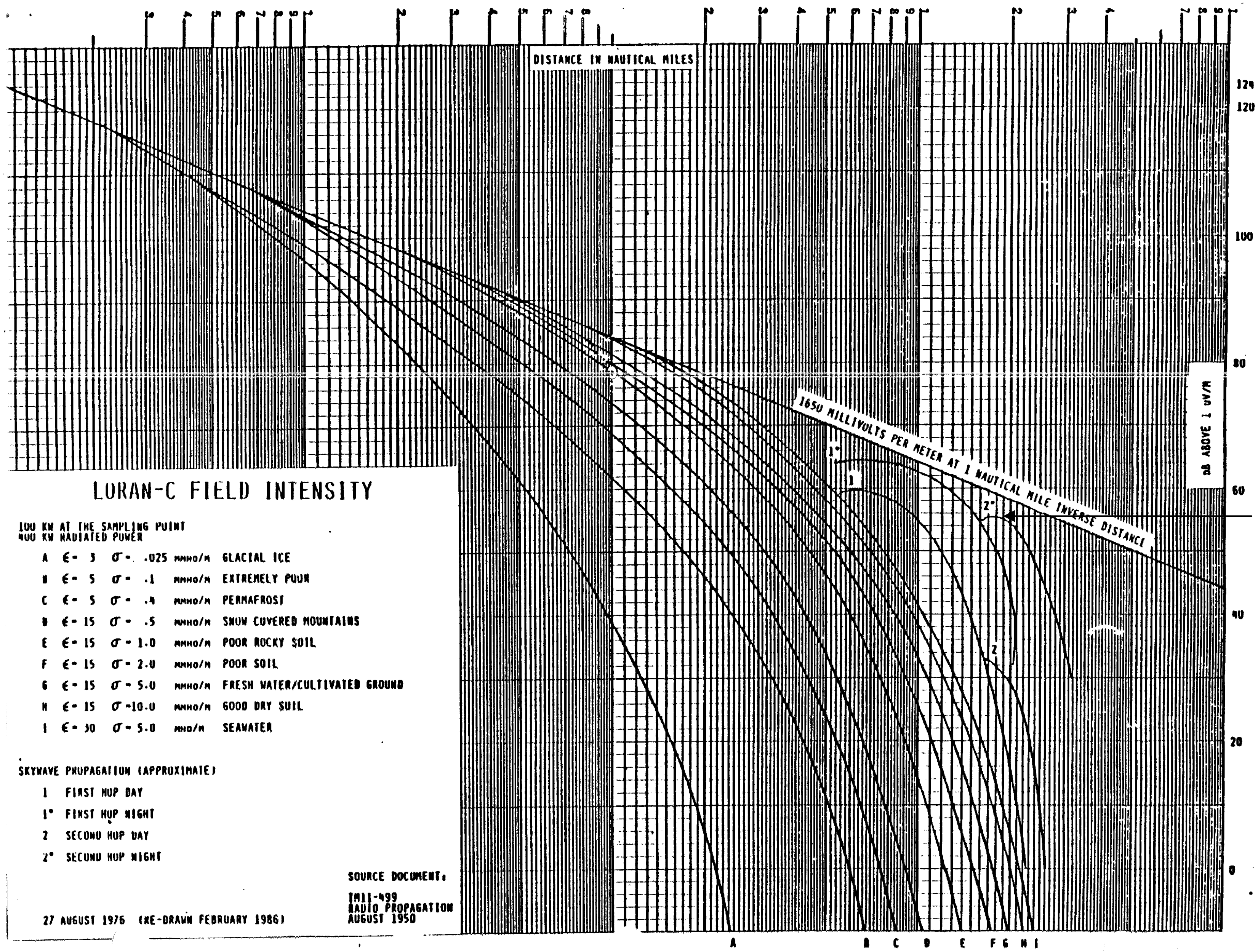
Time difference of Carolina B 2nd Hop Skywave to Dana Groundwave, Min groundwave delay = 800 us, Layer Height = 90 km



Time difference of Carolina B 3rd Hop Skywave to Dana Groundwave, Min groundwave delay = 800 us, Layer Height = 90 km



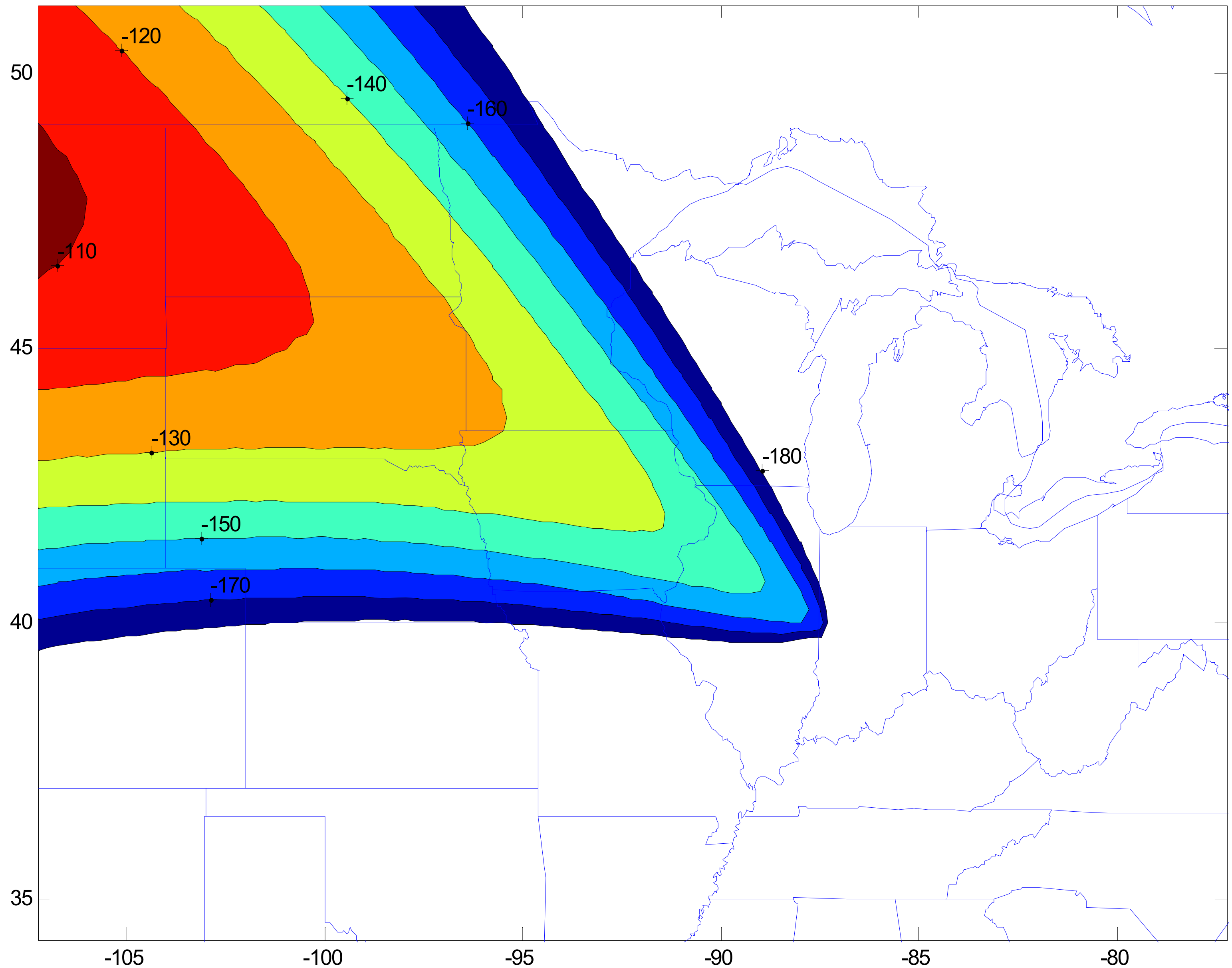
Standard Chart used to Model Skywave Amplitude



2nd Hop Night Skywave

Figure 2 LORAN-C Field Strength vs. Distance

Amplitude of 2nd Hop Skywave Carolina B re Dana   Groundwave, Min groundwave delay = 800 us, Layer Height = 84 km



From "Loran-C Phase Modulation Study, Final Technical Report, Vol. I (June 1970)." by ITT

From operation in Southeast Asia the USCG has photographed the sky waves shown in figures 3-6 through 3-10. This is evidence that multiple hops occur, resulting in strong sky waves that intercept the second and third ground waves in the pulse group. It is shown most graphically by the indicated point on figure 3-7 which shows a sky wave at approximately 1500 microseconds from the last ground wave. The structure of the phase code protects the system against these effects since the code allows a response only when all eight pulses of the group are averaged.

From "Loran-C Phase Modulation Study, Final Technical Report, V. I (June 1970)."
Skywaves or Deccajector??

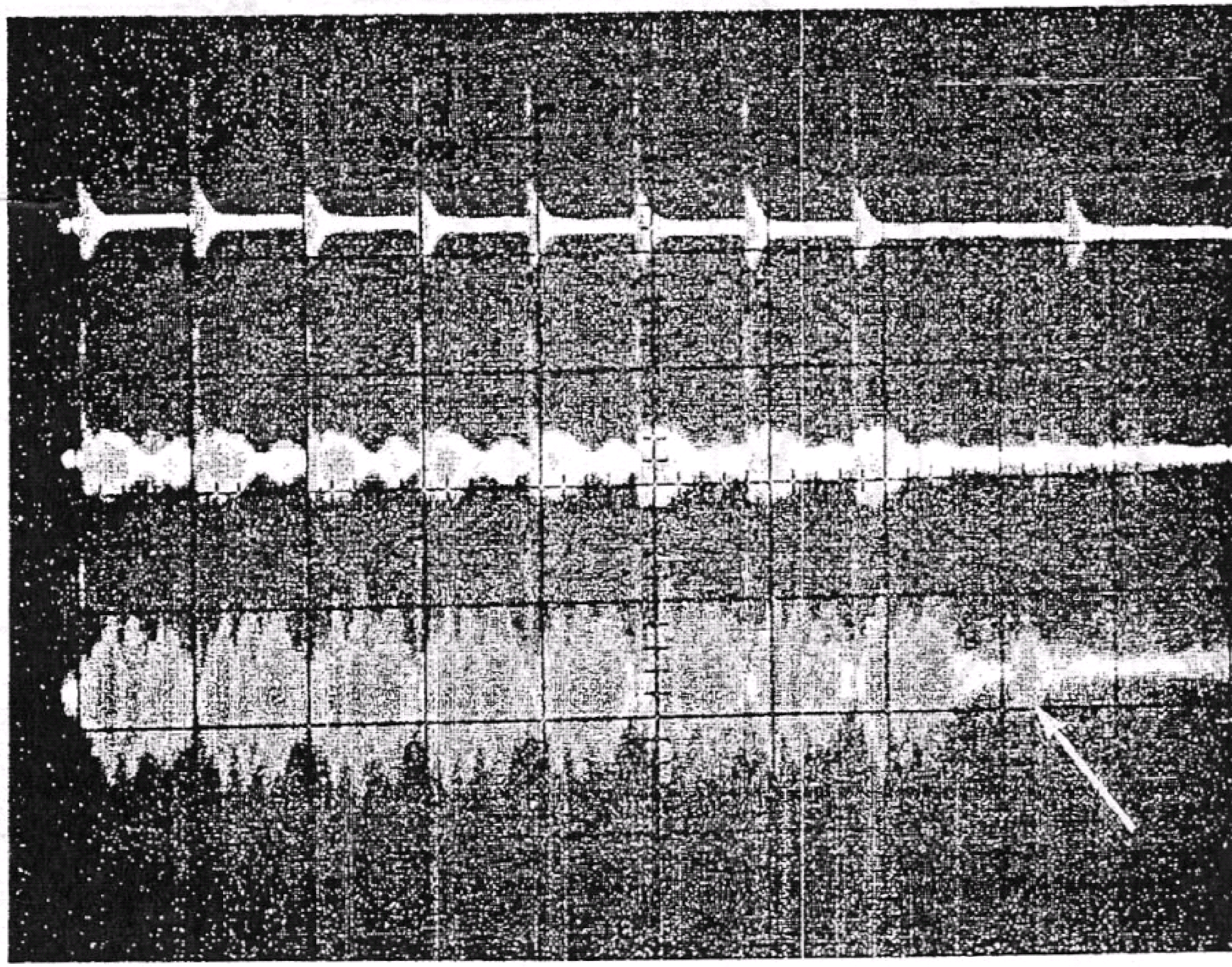
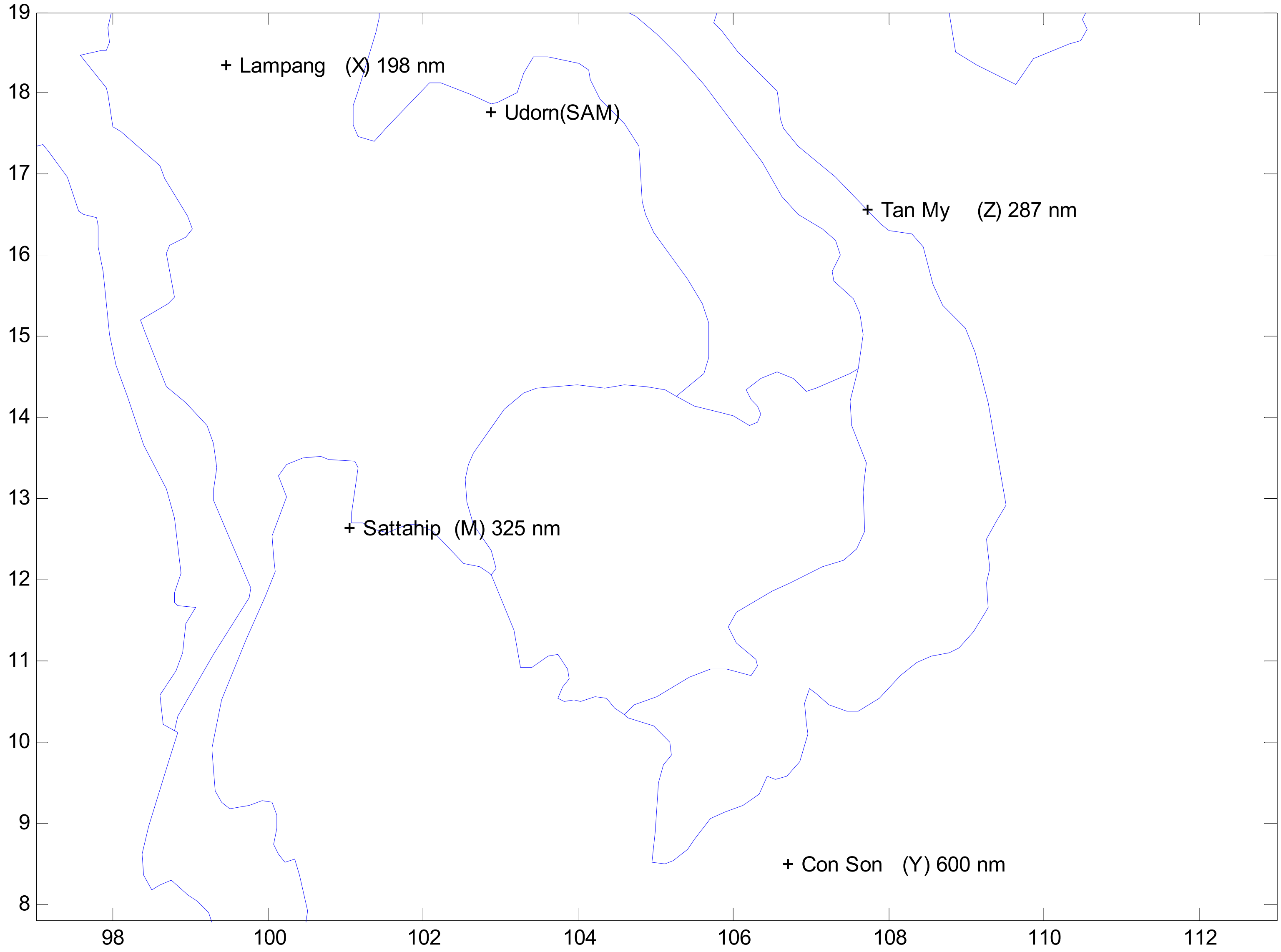


Figure 3-7. Sky Waves in South East Asia (1,000 μsec./cm Sweep Speed) Condition 2

SE Asia Loran (GRI 5970)

Distances are from transmitters to SAM in nm



Example of Terrain Effects on Loran Signal Strength

Current Effort to use Terrain Data in addition to Conductivity for better predictions

From: Benjamin Peterson, Dean Bruckner and Michael Danish, and Peter Morris, "Analysis of Terrain Effects on DGPS and LORAN Signals," **Proceedings of Institute of Navigation National Technical Meeting**, Anaheim, CA, January 2000.

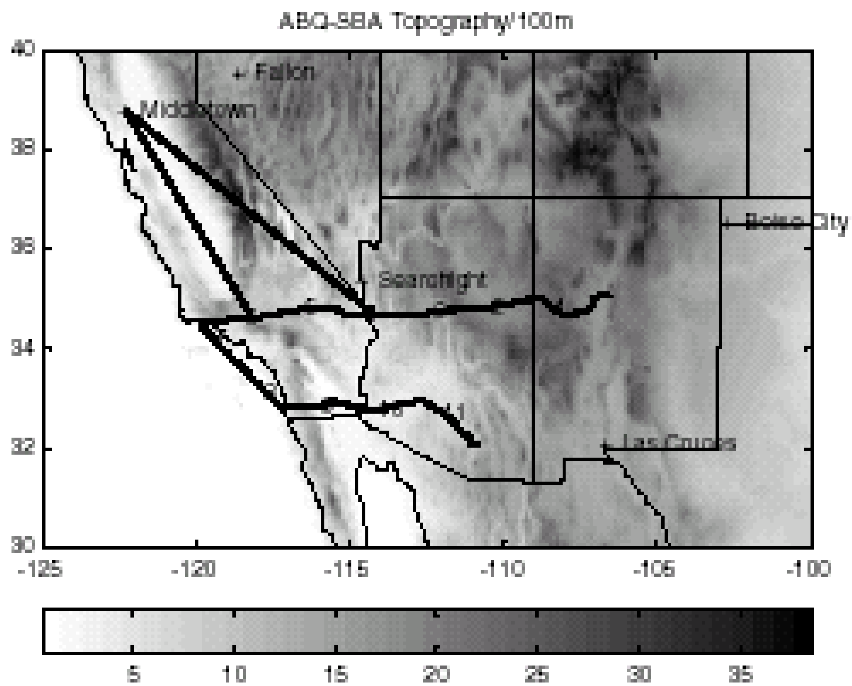


Figure 1: Aircraft track with radial signal paths from LORAN Station Middletown, CA

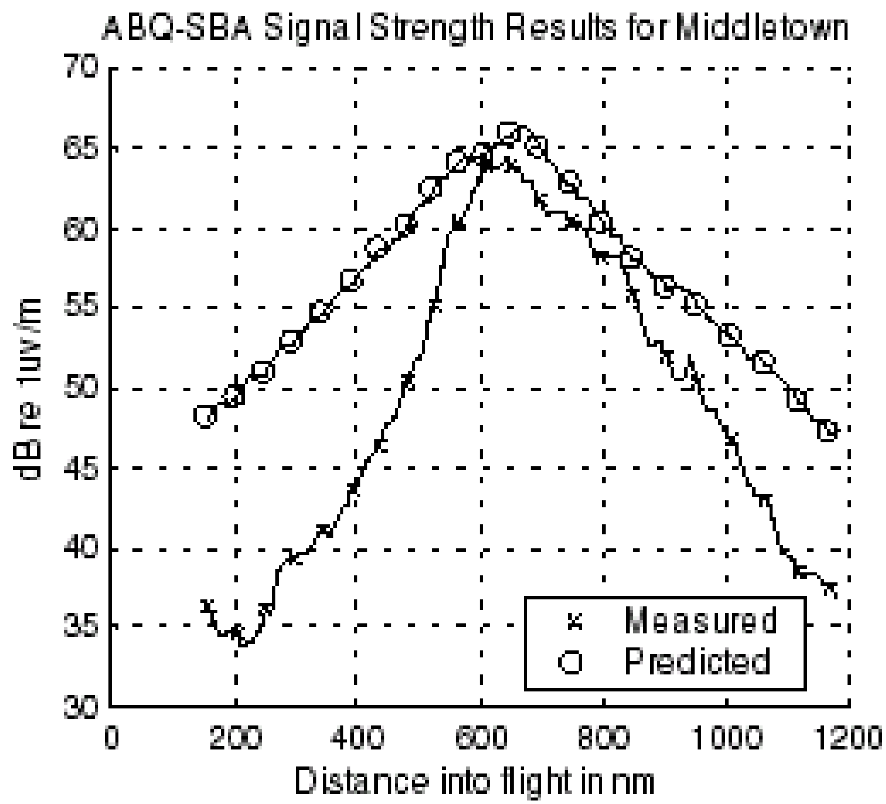
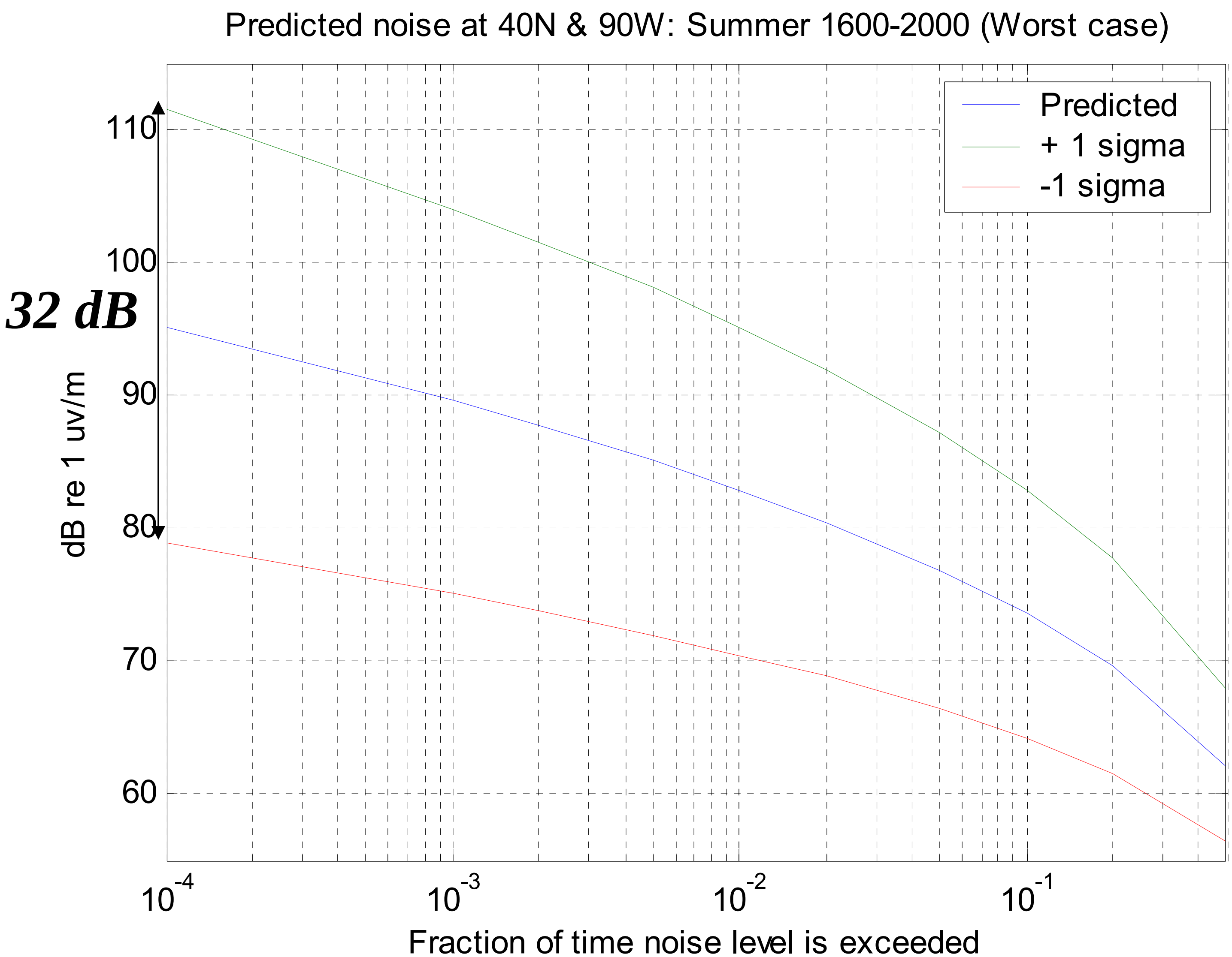


Figure 4: Aircraft measured and predicted signal strengths for LORAN Station Middletown, CA

Confidence in CCIR noise predictions



If a modulated pulses are added, should there be two parallel 24 GRI/epoch channels or one 12 GRI/epoch channel? (except WAAS)

- Information capacity/bandwidth, time to first fix, etc. are not the issue here as both approaches have identical information capacity.
- Single 12 GRI/epoch channel reduces the message duration from a range of 1.42 to 2.4 sec to ½ of this or between 0.71 to 1.2 sec.
  - Advantage in meeting aviation time to alarm requirements.
- Advantages of a multiple 24 GRI/epoch channels
  - Scalability or the ability to only use as much LDC capacity on a particular station as necessary to meet valid requirements.
    - Single pulse format has more than enough capacity to meet all the requirements we have identified. (Except WAAS)
    - Doubling the number of modulated pulses per group within a single message has doesn’t come for free; doubles the cross rate interference generated by the LDC.

Summary

- Analysis suggests that it is feasible to support additional information bandwidth if required on eLoran
  - 2 or more modulated pulses possible on each rate of all dual rated stations in North America
  - 3 or more modulated pulses possible on each single rated station in North America except Las Cruces
    - Enables WAAS channel plus normal LDC channel
- However; just because the potential capacity is there, doesn't mean it should be utilized
  - Every additional modulated pulse contributes to cross rate (that cannot be canceled in avionics) and degrades availabilty
    - To determine exact threshold for how many modulated pulses are acceptable is difficult
  - Agency X will need to weigh benefits of additional messages & degradation of navigation performance

Acknowledgements/Contact Info/Disclaimer

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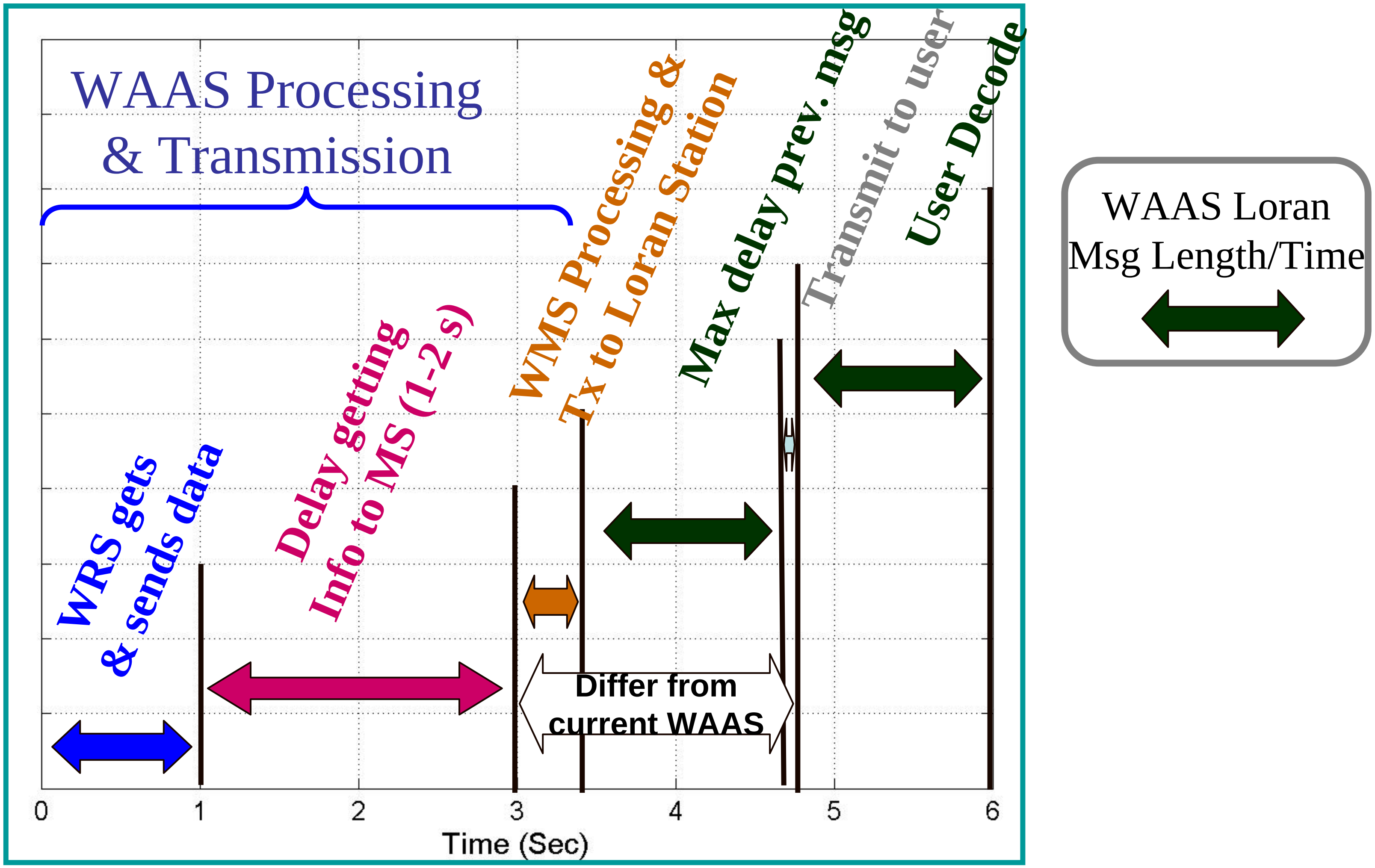
-Note-

The views expressed herein are those of the author and are not to be construed as official or reflecting the views of the U.S. Coast Guard, the U. S. Federal Aviation Administration, or the U.S. Departments of Transportation and Homeland Security.

Background Slides on LDC WAAS Data Channel

(GEAS Brief slides not already included)

WAAS on eLoran – Time to Alarm

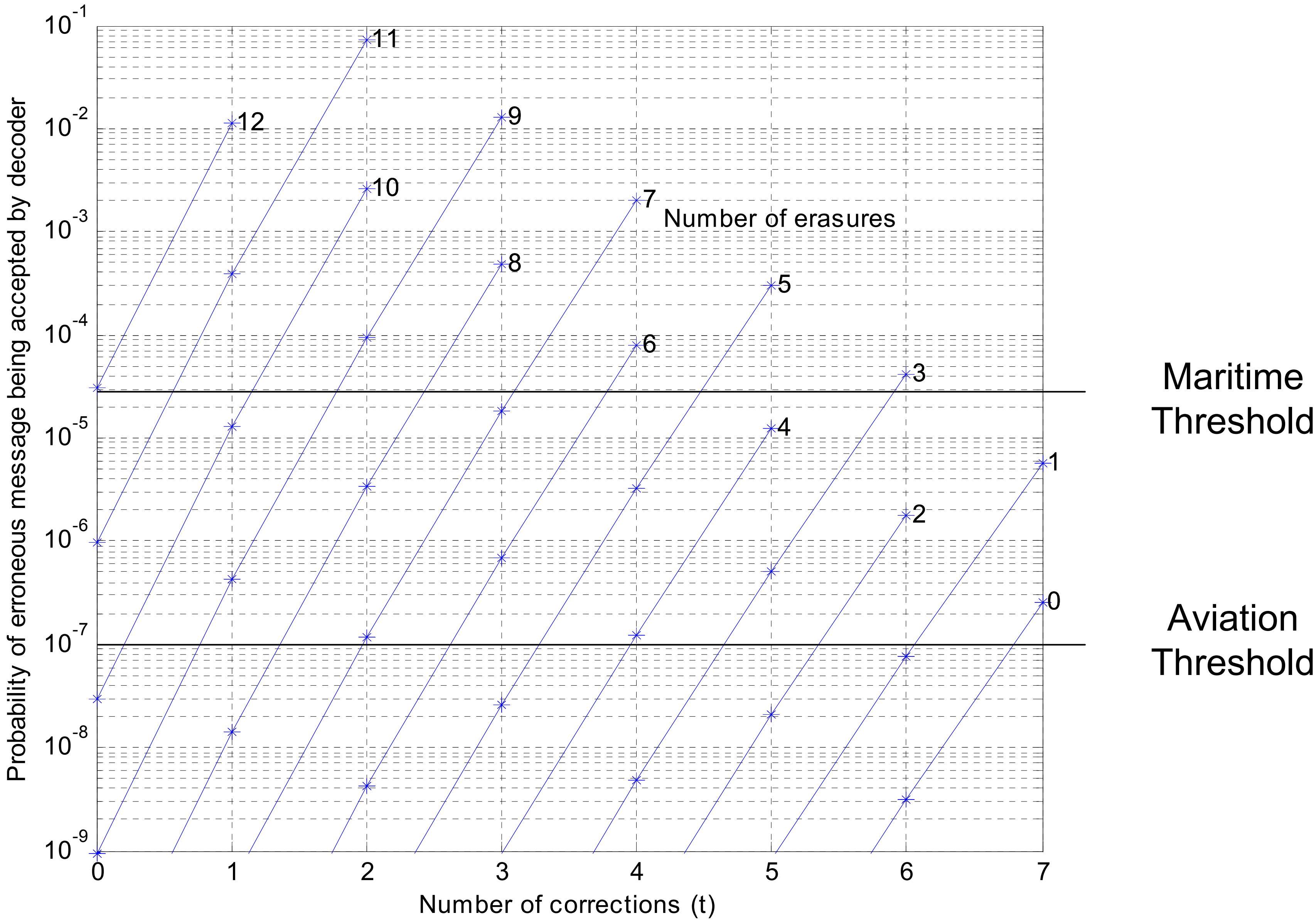


Master Station (MS) Processing & distribution to LorSta time ~ 0.3 seconds
Max message time ~ 1.3 seconds

Message Integrity

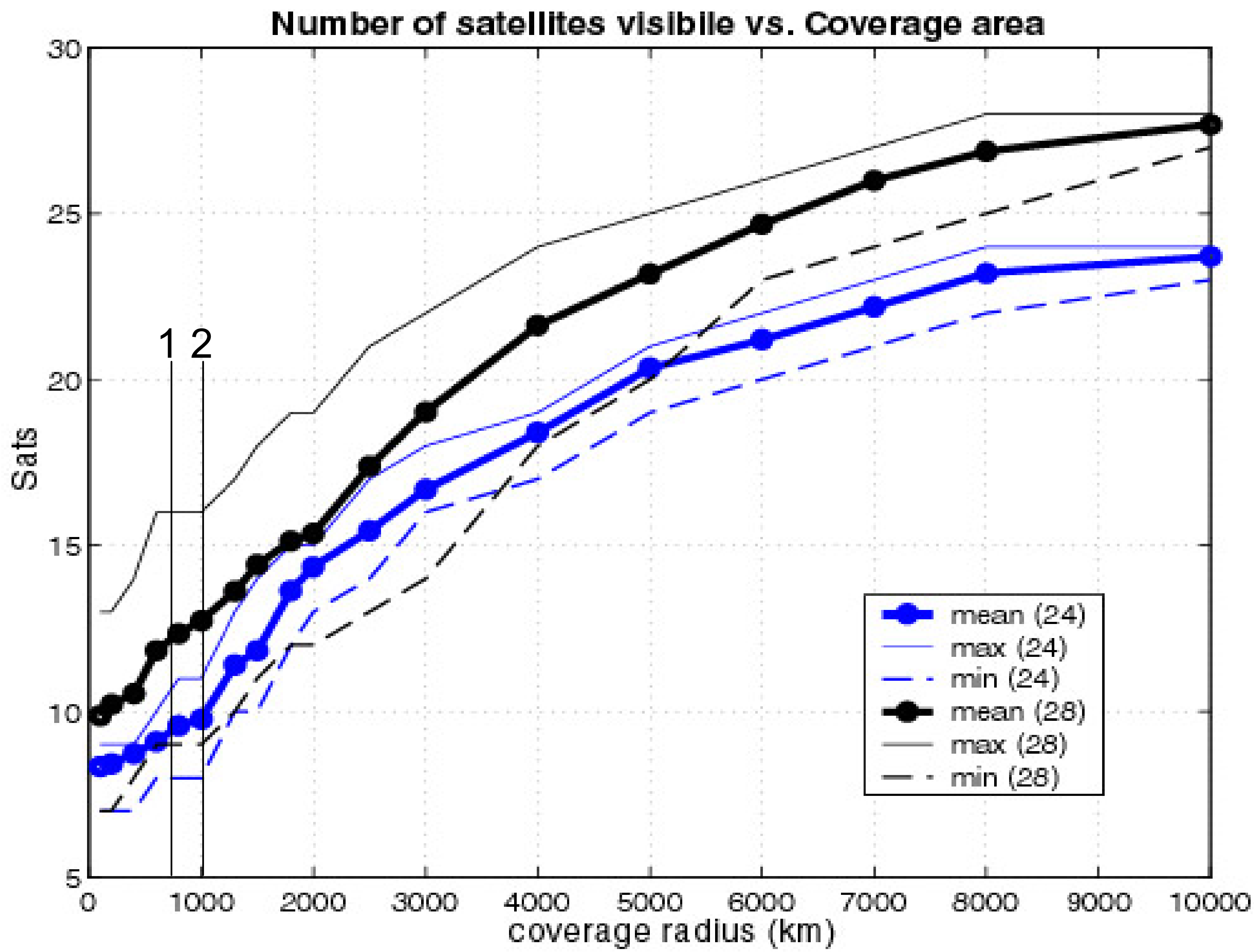
- WAAS uses 24 bit CRC Parity
- "provide protection against burst as well as random errors with a probability of undetected error ≤ $2^{-24} = 5.96 \times 10^{-8}$ for all channel bit error probabilities ≤ 0.5."
- Currently 9th Pulse uses Reed Solomon to provide message integrity
  - Should not require CRC

Message Integrity using Reed Solomon FEC vice CRC



Satellites Visible vs Coverage Area

Note: All of US within 775 km of 1 LORSTA; within 1030 km of 2 (880 & 1200 on North Slope)



- Optimal 24 (RTCA) & 28 satellite August 2000: 5 degree mask

Basic Requirements for Supporting WAAS & Integrity

- Time to Alarm (TTA) must be supported
  - 6 seconds for most stringent WAAS applications
  - WAAS on Loran can meet 6 sec TTA – message length limited to < 1.3-1.4 seconds
- Message Integrity (CRC, etc.)
  - Guarantee message is correct with probability $< 10^{-7}$ of being accepted if incorrectly received/decoded
  - FEC will be used for message alignment & integrity in eLoran
- Data
  - Integrity Info (WAAS Type 6)
  - Fast Corrections (WAAS Type 2-4)
  - Long Term Corrections (WAAS Type 25)
  - Degradation Messages (WAAS Type 7, 10)

“Minimum” Data Requirements

- Satellite Mask
- Integrity Flag: 4 bits
  - Current UDRE is 4 bits, update every 6 sec
- Fast Corrections
  - 12 bits, update probably ~ 60 sec
- Long Term Corrections
  - Velocity code = 0, 51-54 bits per satellite, update 120 sec
  - Velocity code = 1, 103-105 bits per satellite, update 120 sec
- Degradation Parameters
  - Type 10: 7 parameters ~ 10 bits each (64 bits total) , update 120 sec
  - 4 bit UDRE degradation per satellite, update 120 sec

Proposed Design Overview

- 120 raw bits resulting in 45 bit messages
  - .71 to 1.2 seconds per message
  - No CRC, header
  - Reed Solomon provides alignment, message integrity
- 64 message types
  - PRN/SVN indicated by message type
- Differences from Current WAAS data format
  - Fast Correction Resolution Changed to 9 bits (-32 to 31.875 m)
  - UDRE changed to 3 bits

Design Details

- Msg 1-2: Mask
- Msg 3-8: Fast Corrections
  - Fast Correction Dynamic Range Changed to 9 bits (-32 to 31.875 m)
  - 4 satellites per correction
- Msg 9-11: UDRE
  - 3 bit UDRE, 12 satellites
- Msg 12-31: Long Term Corrections
  - No Velocity, IOD given in another message
- Msg 32: IOD message for LT Corrections
- Msg 33-34: UDRE Degradation Msg
- Msg 35-36: Degradation Msg

Proposed Design Message Types

Message Types	# of Msg Type	Bits per Sat	Sats per Msg	Max BW Used
Mask	1	1	36	1.00%
UDRE	2	3	12	40.00%
Fast	5	9	4	10.00%
LT	20	36	1	20.00%
UDRE degrad	2 (up to 40 bits)	3	12	2.00%
Degradation	2	N/A	N/A	2.00%
UDRE Flag	1	1	40	1.00%
IOD	1	N/A	N/A	1.00%
Total	33			76.00%

6 bits message type, 3 bits for IODF, etc.

Bandwidth Utilization Study

Message Info	Min Msg Type Req.	Max Msg Type Req.	Min Bits per Sat	Max Bits per Sat	Min BW Used	Max BW Used
Mask	2	2	1	1	2.0%	2.00%
UDRE	2	3	3	4	40.0%	60.0%
Fast	5	7	8	12	10.0%	14.0%
LT	20	20	36	36	20.0%	20.0%
UDRE degrad	2	3	3	4	2.0%	3.0%
Degrad	2	2	N/A	N/A	2.0%	2.0%
IOD	1	1	N/A	N/A	1.0%	1.0%
Total	34	38			77.0%	102.0%

- Need to have BW utilization < 90% so some messages can have priority
- Potentially reduce BW usage by having a UDRE Flag message flagging the continued use of the present UDRE set
- BW reduction from UDRE necessary in the design

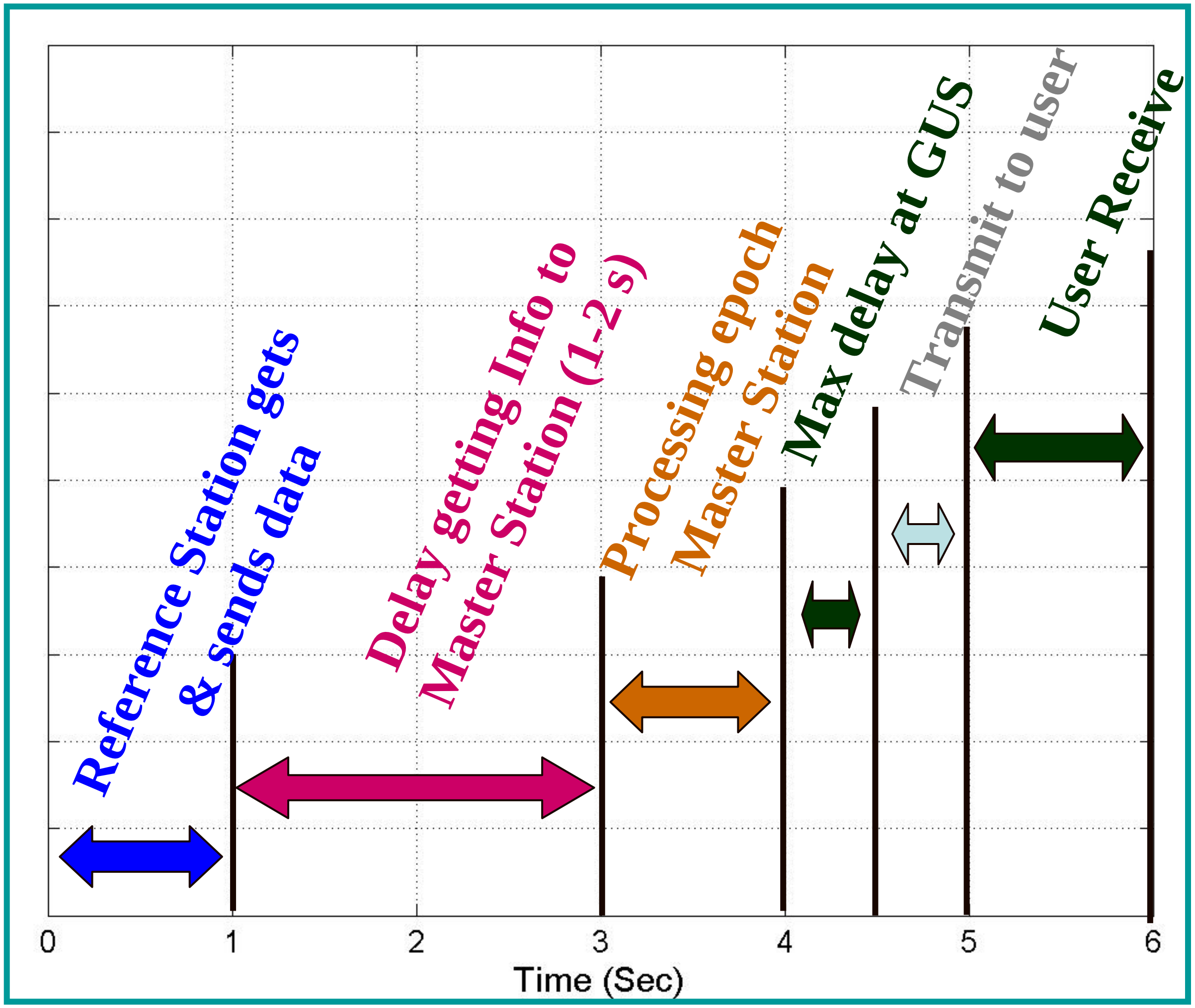
Issues & Limitations

- Design & Implementation Issues
  - Will long term corrections with velocity be necessary?
    - May reduce dynamic range of correction
  - Ensure that the correct UDRE, Fast & Long Term corrections are used together - IODx

Current WAAS Messages

Correction Type	Message Type(s)	Messages per Update Interval	Update Interval (sec)	Percent of Full Bandwidth
Satellite Mask	1	1	60	1.7%
Fast Corrections	2-4	2	6	33.3%
Fast Corrections (others)	5	0	60	0.0%
UDRE Update	6	0	6	0.0%
Fast Degradation	7	1	120	0.8%
Geo Navigation	9	1	120	0.8%
UDRE Degradation	10	1	120	0.8%
UTC/WAAS	12	1	300	0.3%
Geo Almanac	17	1	300	0.3%
Ionosphere Grid Mask	18	4	300	1.3%
Mixed Corrections	24	1	6	16.7%
Long-term Corrections	25	0	120	0.0%
Ionosphere Corrections	26	25	300	8.3%
WAAS Service	27	0	300	0.0%
UDRE modification	28	~10?	120	8.3%
Total				71.2%

WAAS Integrity Alarm Timeline



Purpose of WAAS IOD

- **A.4.4 Messages and Relationships Between Message Types**
- Table A- 3 presents the set of message types. Unless otherwise stated, data is
- represented in unsigned binary format.
- In order to associate data in different message types, a number of issue of data (IOD) parameters are used. These parameters include:
  - IODk (GPS IOD Clock - IODCk, GPS IOD Ephemeris - IODEk,GLONASS Data - IODGk): Indicates GPS clock and ephemeris issue of data or GLONASS clock and ephemeris issue of data, where k = satellite
  - IOD PRN Mask (IODP): Identifies the current PRN mask
  - IOD Fast Correctionsj (IODFj): Identifies the current fast corrections, where j = fast corrections Message Type (Types 2 - 5)
  - IOD Ionospheric Grid Point Mask (IODI): Identifies the current Ionospheric Grid Point mask
  - IOD Service Message (IODS): Identifies the current Service Message(s) Type 27

- The relationship between the messages is shown in Figure A- 7. The IOD's (including GPS IODC and IODE and GLONASS IODG - TBD) are specific to each satellite, and are updated separately. There is only one active PRN mask, one Ionospheric Grid Point mask, and one active set of Service Messages. Since fast corrections are always provided in different message types including blocks of 13 satellites, a different IODF is used for each block. Note that the WAAS will ensure that the long-term corrections are sent several times when modified, and the magnitude of the change will be small so that an issue of data is not necessary to connect Type 24 or 25 and Type 2 - 5 messages. In addition, the WAAS will update long term corrections at a rate high enough to accommodate these small changes, while also accommodating missed messages by the users.

Interrelationship between WAAS Messages

Appendix A
Page 21

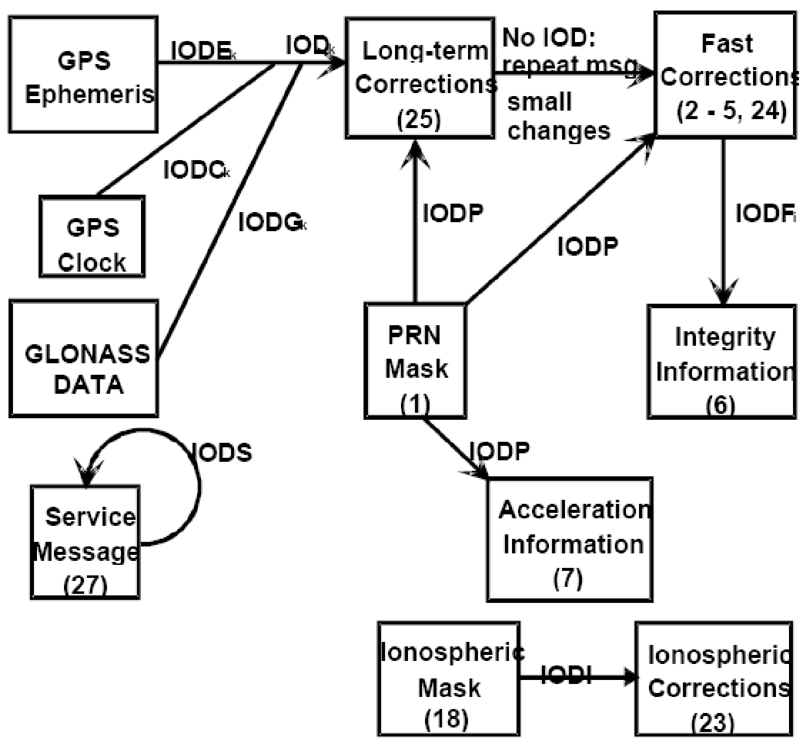


Figure A- 7 INTERRELATIONSHIPS OF MESSAGES

WAAS Long Term Corrections (without Velocity)

Parameter	No of Bits	Scale Factor (LSB)	Effective Range	Units
PRN Mask	6	1	0 to 51	—
Issue of Data	8	1	0 to 255	discrete
δx (ECEF)	9	0.125	±32	meters
δy (ECEF)	9	0.125	±32	meters
δz (ECEF)	9	0.125	±32	meters
δa_{f0}	10	2^{-31}	$\pm 2^{-22}$	seconds

Relevant WAAS Degradation Parameters

Parameter	No of Bits	Scale Factor (LSB)	Effective Range	Units
B_{rrc}	10	0.002	0 to 2.046	m
C_{ltc_v0}	10	0.002	0 to 2.046	m
I_{ltc_v0}	9	1	0 to 511	s
C_{er}	6	0.5	0 to 31.5	m
RSS_{UDRE}	1	-	0 to 1	discrete
System Latency (t_{lat})	4	1	0 to 15	s
Degrad factor indicator (ai_i)	4	1	0 to 15	Provides I_{fc}, a

From Type 7 Message

* Include in degradation message

WAAS Long Term Corrections (without Velocity)

Parameter	No of Bits	Scale Factor (LSB)	Effective Range	Units
B_{rrc}	10	0.002	0 to 2.046	m
C_{ltc_v0}	10	0.002	0 to 2.046	m
I_{ltc_v0}	9	1	0 to 511	s
C_{er}	6	0.5	0 to 31.5	m
RSS_{UDRE}	1	-	0 to 1	discrete
C_{ltc_lsb}	10	0.002	0 to 2.046	m
C_{ltc_v1}	10	0.00005	0 to .05115	m/s
I_{ltc_v1}	9	1	0 to 511	s

ONLY NECESSARY FOR VELOCITY CODE = 1

Summary

- Analysis suggests that it is feasible to support WAAS on eLoran
  - 9^{th} and 10^{th} pulse resulting in 45 bit message every 1.2 sec or less
  - No iono or S/A support, reduced UDRE resolution
  - Operational infrastructure change also necessary (direct line from WMS to each LorSta)
- Message Design
  - Compatible with current 9^{th} pulse support of NPA, HEA, timing
  - Other designs possible
- Design and analysis preliminary
  - Still some issues to work but should be surmountable