Avionics Engineering Center

The Loran Propagation Model: Development, Analysis, Test, and Validation

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ILA-37 London, UK October 2008

Introduction

- Accurate navigation using Loran requires precise timing of received signals.
- Mis-modeling or erroneous measurements of Additional Secondary Factors (ASFs), can lead to significant timing errors.
- To support RNP 0.3 for non-precision approach and landing, the timing error no greater than 1 μsec as been established as a metric.
- This requirement can be met by providing accurately measured or predicted ASF values for each airport to the Loran receiver.
- For enroute navigation, error tolerances are more lenient, but ASF values over a larger area must be available.
- Hence a large-scale ASF map of predicted ASF values can be used by the Loran receiver to support aviation.

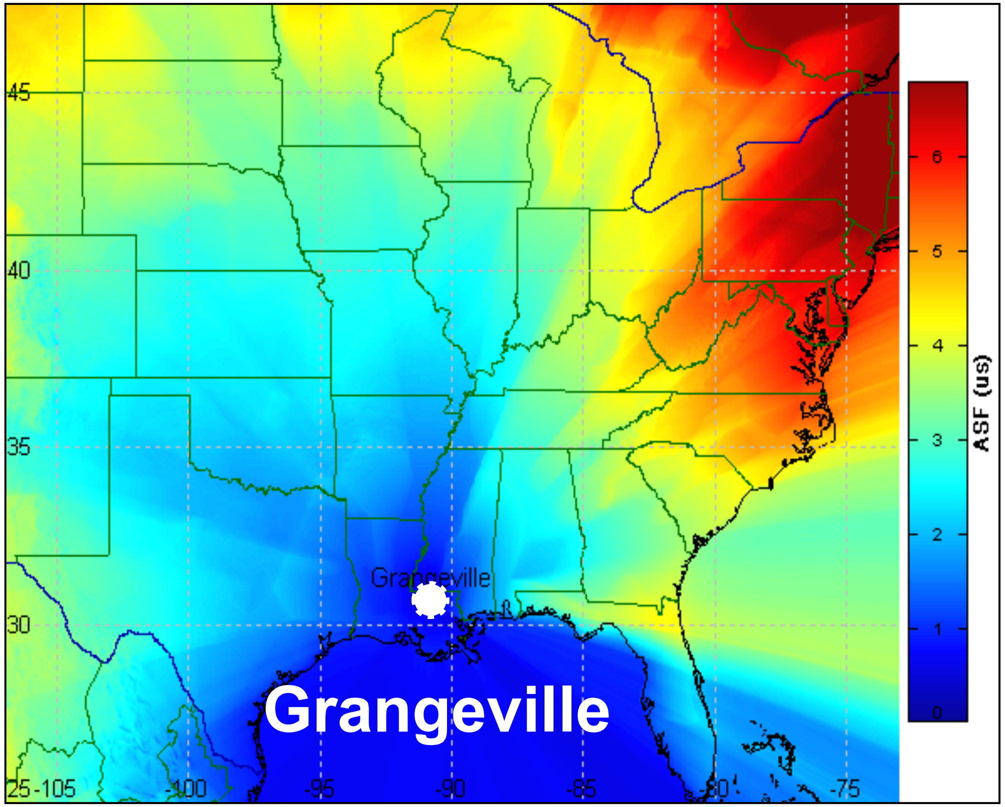
Additional Secondary Factors (ASFs)

- The Loran signal may propagate over a great distance, primarily as a groundwave.
- Delays due to propagation through the atmosphere and over a spherical, seawater surface are accounted for by the primary factor (PF) and secondary factor (SF), respectively.
- ASF delays are affected by:
  - Ground conductivity (the most significant factor)
  - Changes in terrain elevation
  - Receiver elevation
  - Temporal changes (seasons, time-of-day, local weather)
- Additionally, various other factors such as system timing errors or measurement system errors will be included in any measured or perceived ASF values.

Loran Propagation Model (LPM)

- Computer program to predict ASFs over an area or for specified points (i.e., from a particular Xtm to user).
- Formerly known as BALOR.
- Originally developed by Paul Williams and David Last.
- Maintained and improved by Ohio University since 2005.
- Models Loran groundwave propagation using a set of classic equations.
- Performance needs to be validated to support RNP 0.3 requirements.

LPM ASF grid map for Grangeville



TOA Measurement System (TMS)

- System to accurately measure the time of arrival (TOA) of Loran signals with respect to UTC time.
- Developed by Reelektronica.
- Utilizes LORADD eLoran receiver, NovAtel OEM-G2 GPS receiver, and GPS-disciplined rubidium clock.
- A simulated Loran pulse is injected into the antenna
- Calibrated Loran H-field antenna to minimize heading-dependent error.
- A small timing offset is possible since the time of transmission (TOT) is not known.

The TMS rack-mounted in Ohio University's King Air C90 Aircraft

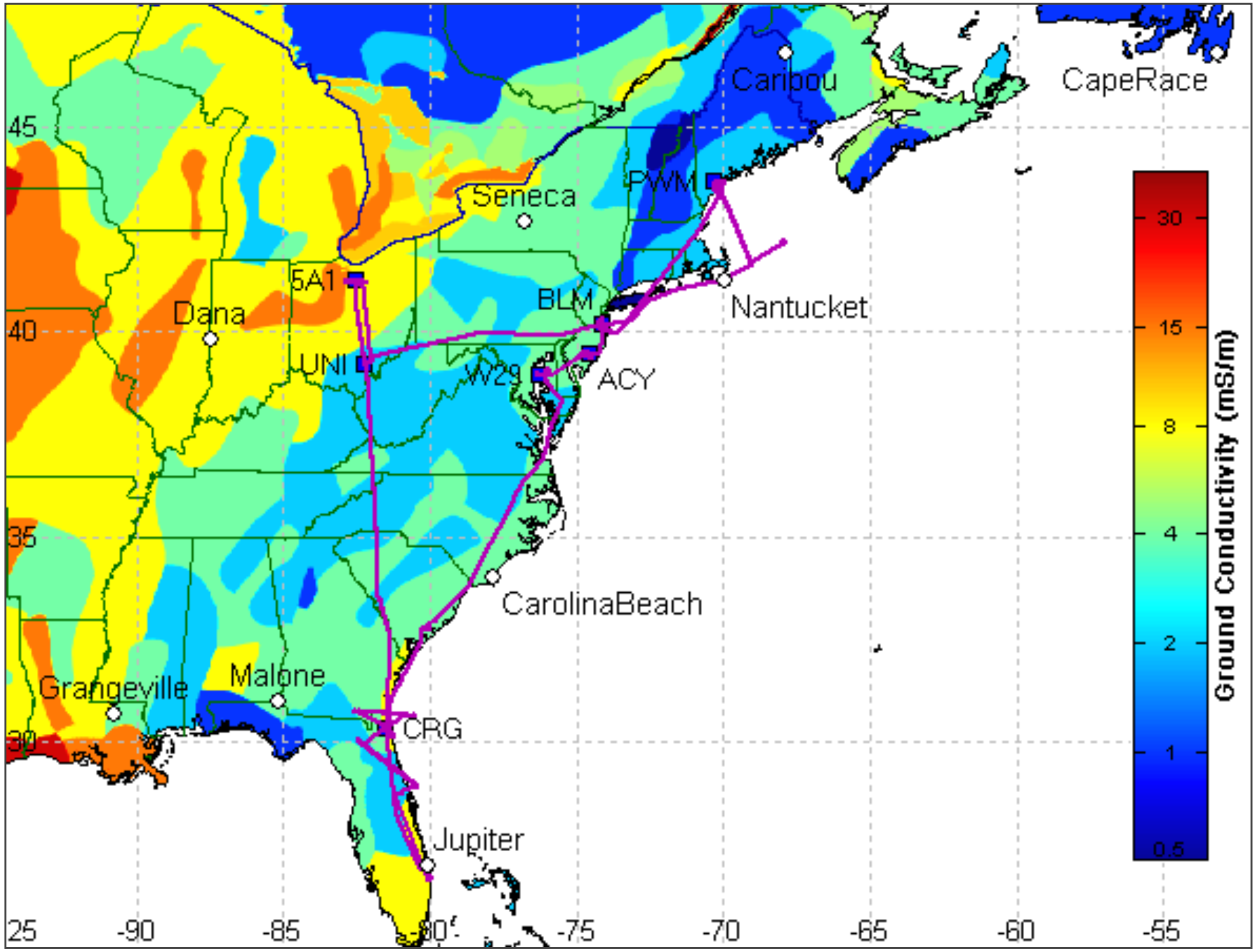
Data Collection Flights – April 14-18, 2008

- Five days of flights over the eastern United States
- Flights included:
  - Approaches at certain airports
  - Enroute legs between airports
  - Flights over ocean and coastlines
  - Altitude tests
  - Calibration circles
- Loran and GPS data were collected throughout all flights using the TMS.
- ASFs predicted by LPM for the same locations were plotted with TMS values for comparison.

Significant airports

Airport Name	ID	Location
Ohio University Airport	UNI	Albany, Ohio
Norwalk-Huron County Airport	5A1	Norwalk, Ohio
Craig Municipal Airport	CRG	Jacksonville, Florida
Bay Bridge Airport	W29	Stevensville, Maryland
Atlantic City International Airport	ACY	Atlantic City, New Jersey
Monmouth Executive Airport	BLM	Belmar/Farming-dale, New Jersey
Portland International Jetport	PWM	Portland, Maine

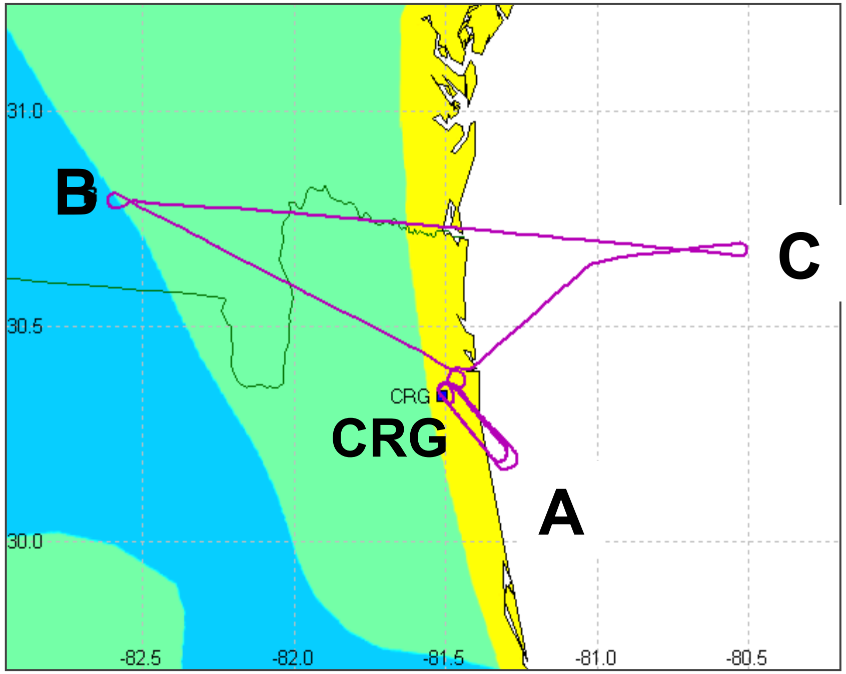
Map of Data Collection Flight Route



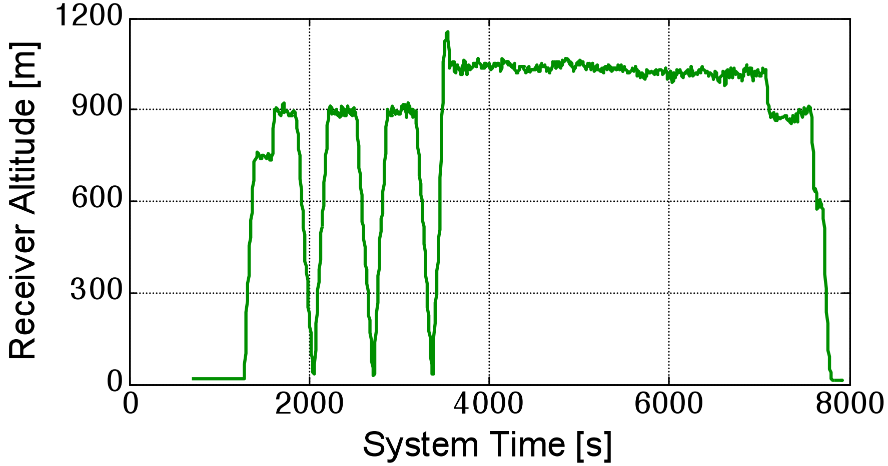
- Key airports and Loran Xtms shown
- Background illustrates ground conductivity.
- 12 separate flights, 8 transmitters tracked at a time

Flight 4 – Craig Municipal Airport (CRG) Vicinity

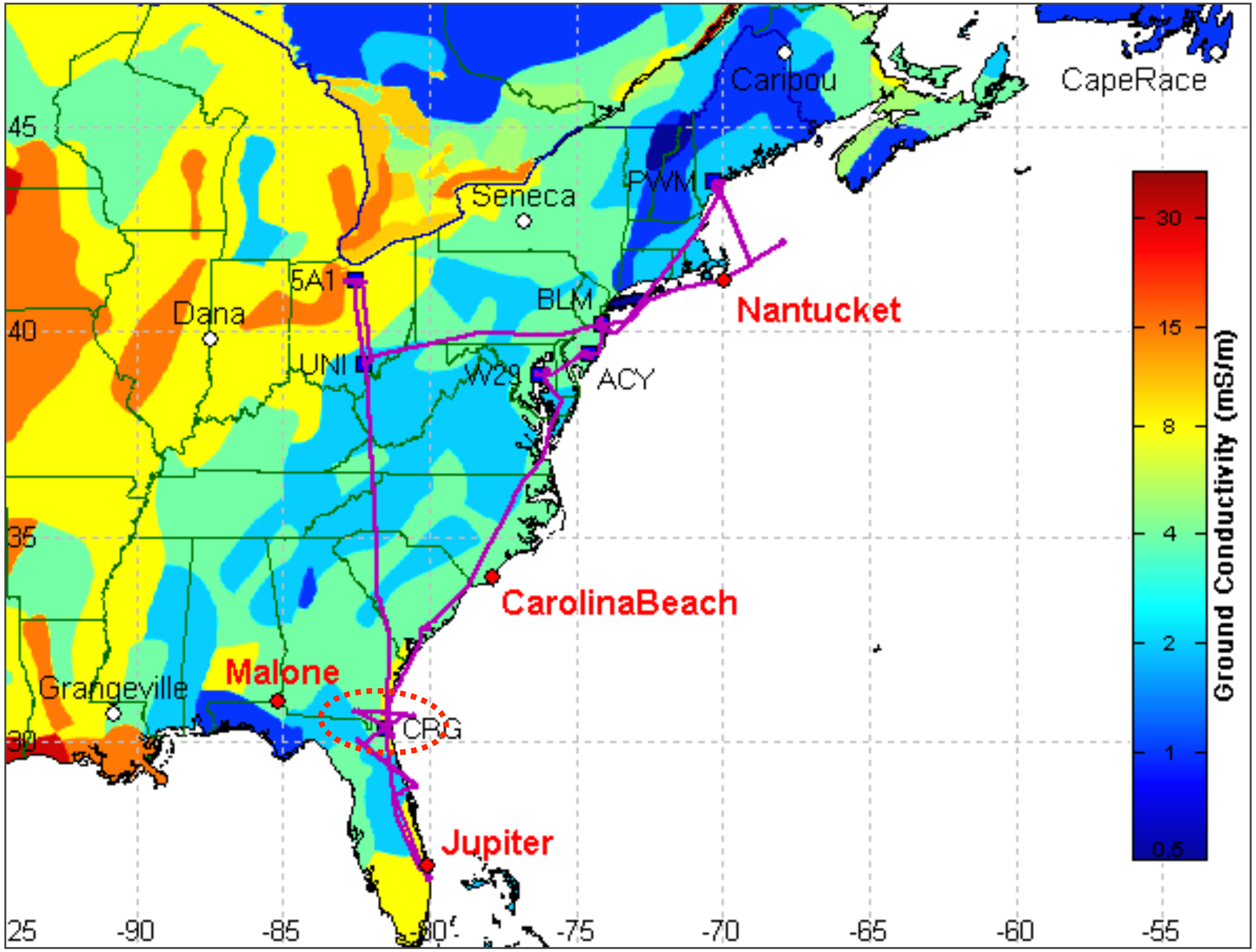
- Approaches at CRG (racetrack between CRG and Point A)
- Inland to Point B
- Across coast to Point C (along radial from Malone)
- Back to land at CRG



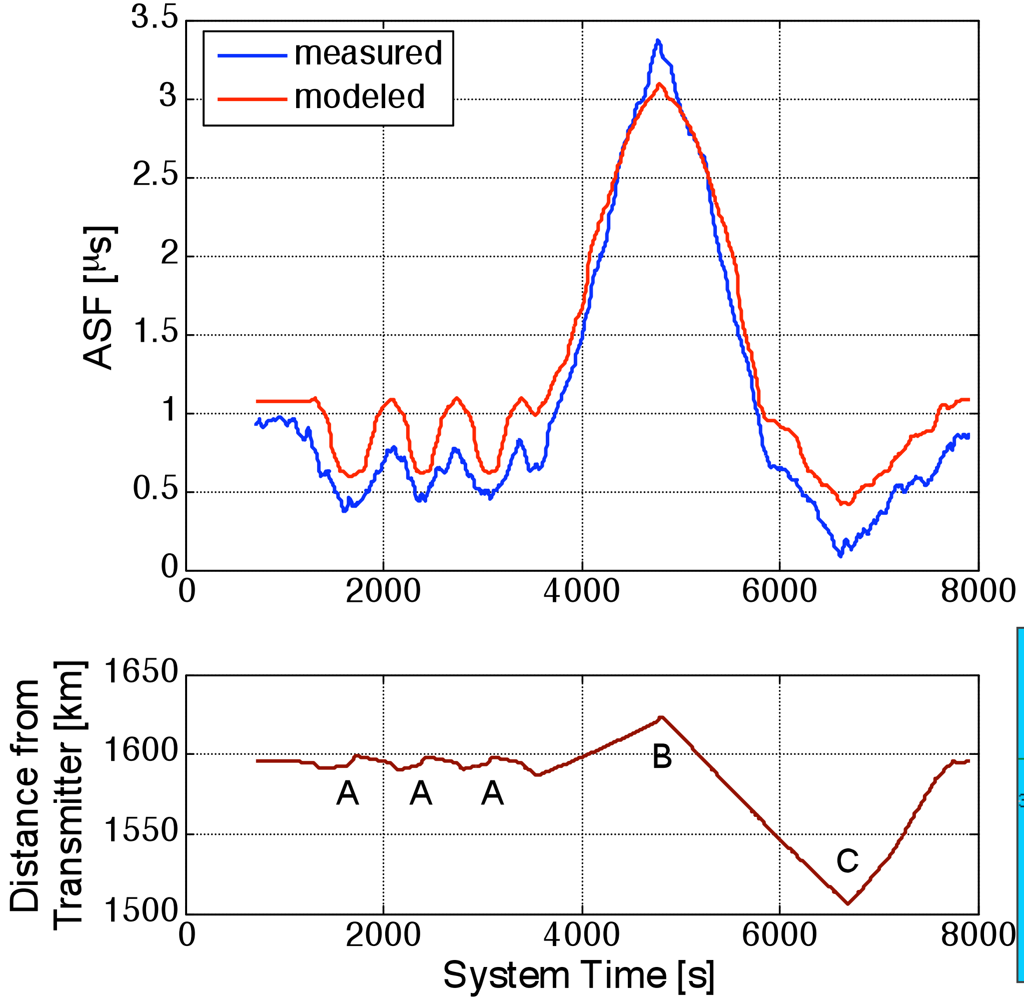
Flight 4 – Altitude



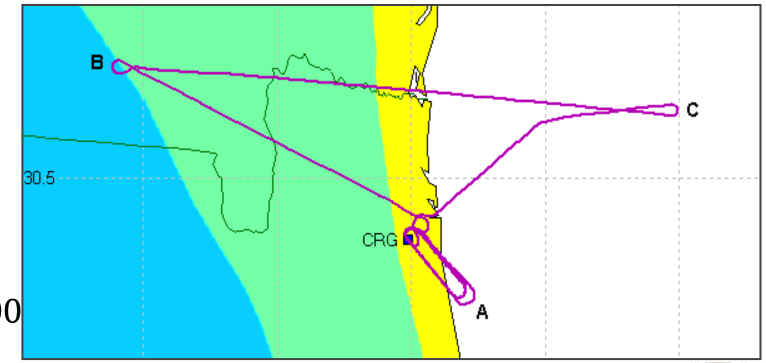
Flight 4 – CRG Vicinity to Various Loran Xtms



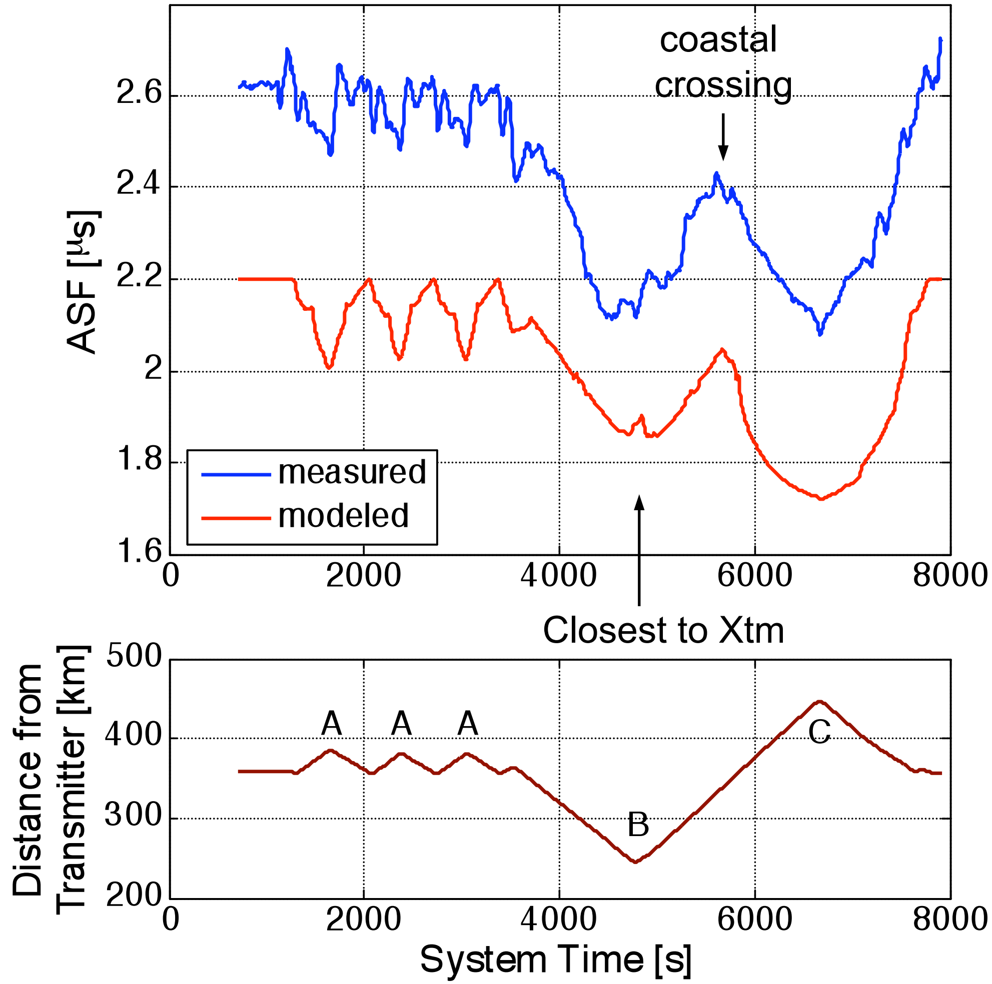
Flight 4 Results – Nantucket, MA



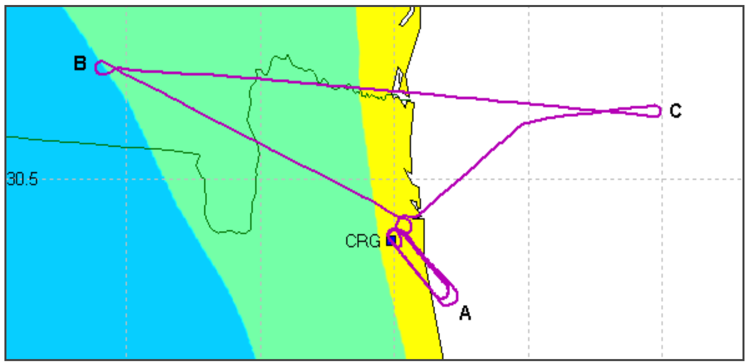
- Path from Xtm is long, but mostly over the ocean.
- The large central peak corresponds to paths having a significant land portion.
- Differences are in the range of 0.2 to 0.3 μs.
- Other plot features are



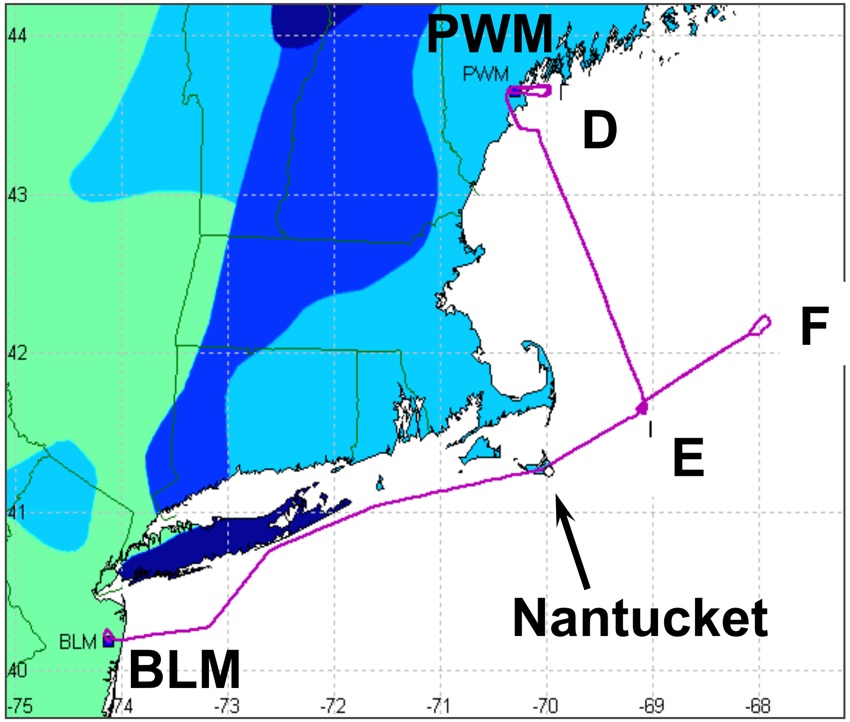
Flight 4 Results – Malone, FL

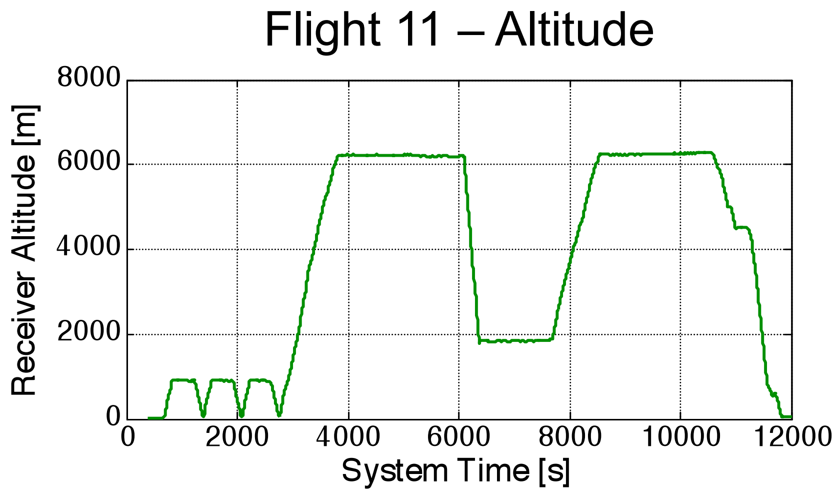


- Path from Xtm is relatively short, but almost all over land.
- Measured and modeled results agree fairly well for shape, but there is an offset of 0.4 μs.
- Peak ~ 5800 corresponds to coastal crossing.



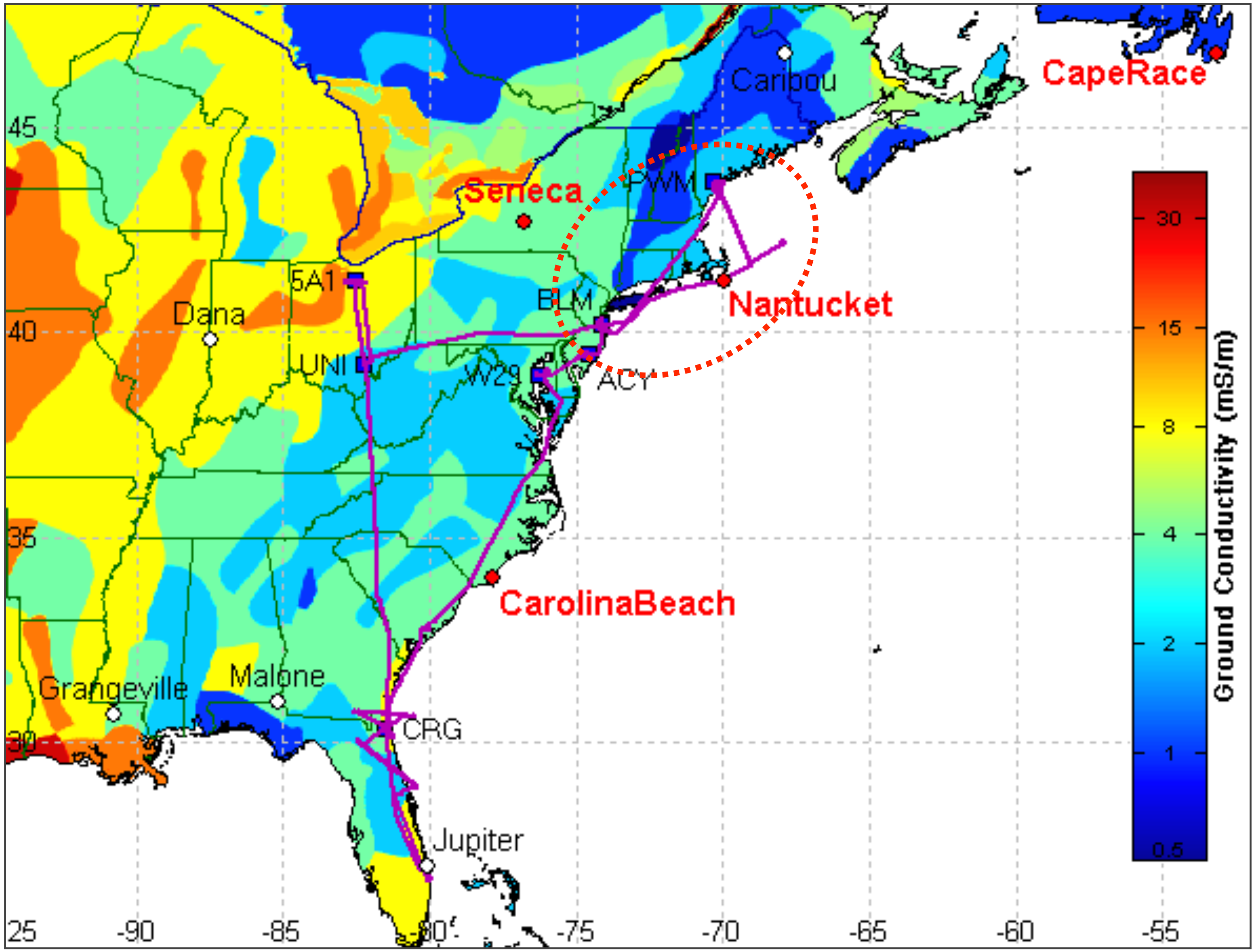
Flight 11 – Portland International Jetport (PWM) to Monmouth Executive Airport (BLM) via Nantucket



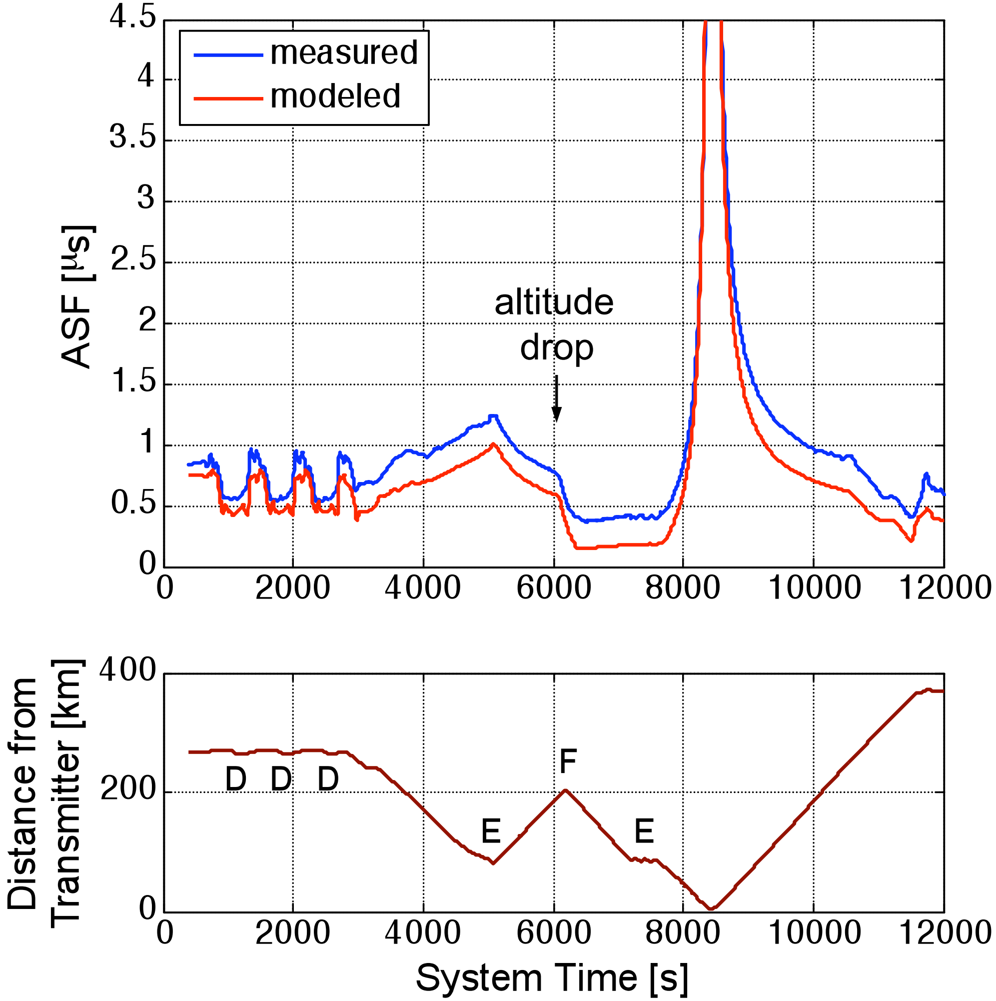


- Approaches at PWM
- Over ocean to point E
- Out to point F at 6000 m
- Descend to 2000 m
- Return to point E
- Climb to 6000 m again
- Pass over Nantucket
- Continue on to touchdown at BLM

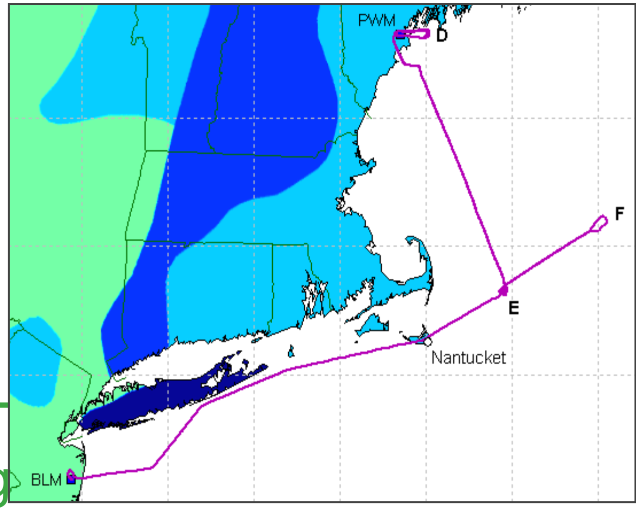
Flight 11–PWM to BLM via Nantucket to Loran Xtms



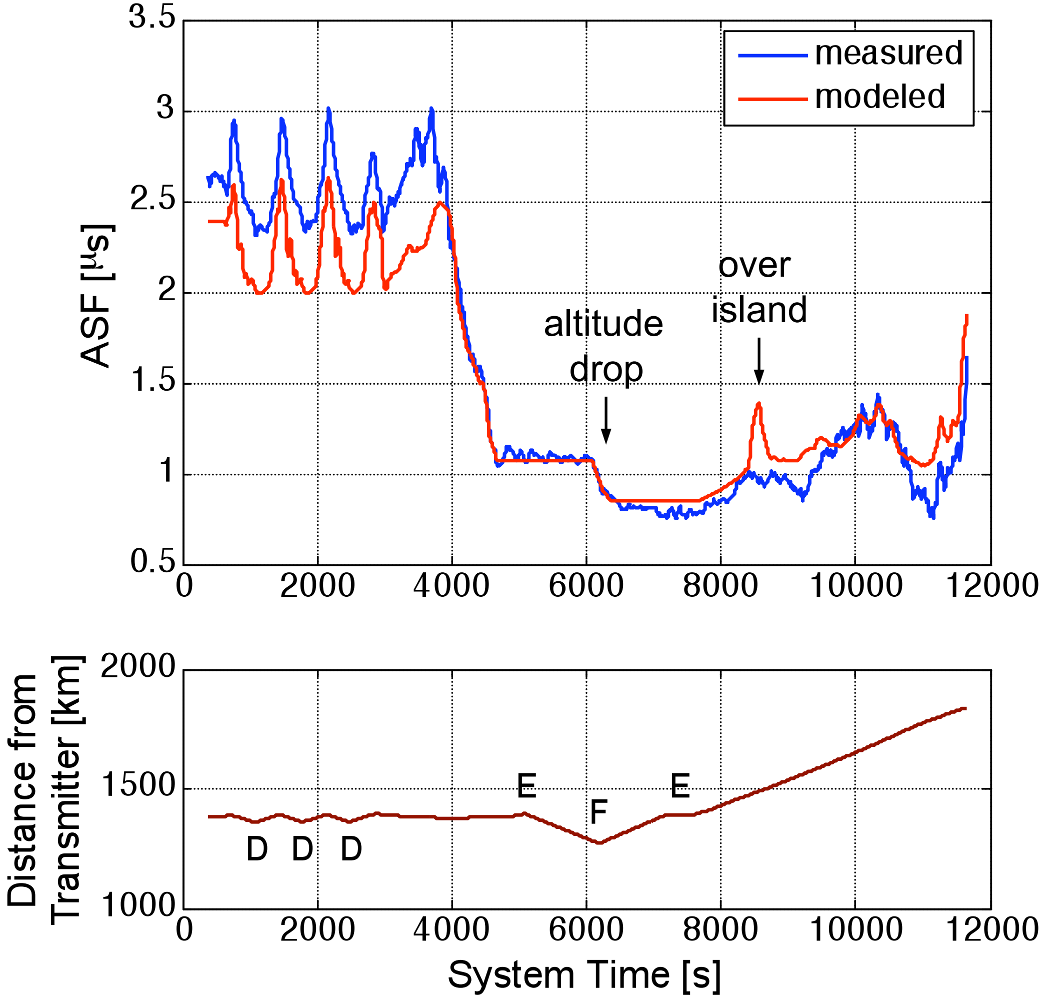
Flight 11 Results – Nantucket, MA



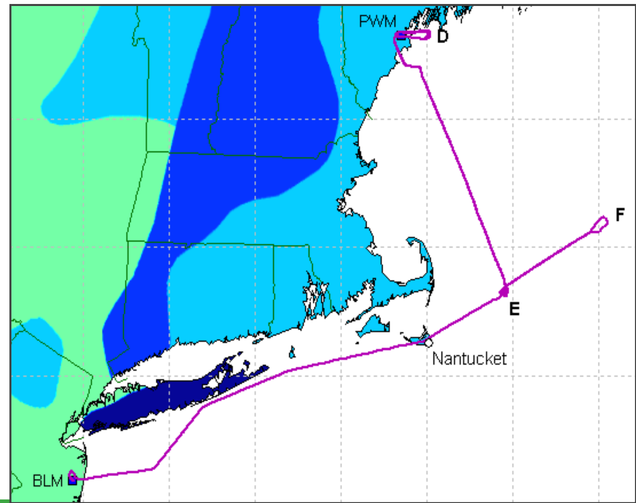
- The path from the Xtm is short; mostly over seawater.
- Large peak ~ 8500 and smaller peak ~ 5000 when the aircraft within 4.3 km and 82 km of the Xtm.
- Match between LPM and TMS results is excellent except for an offset of 0.2 μs.



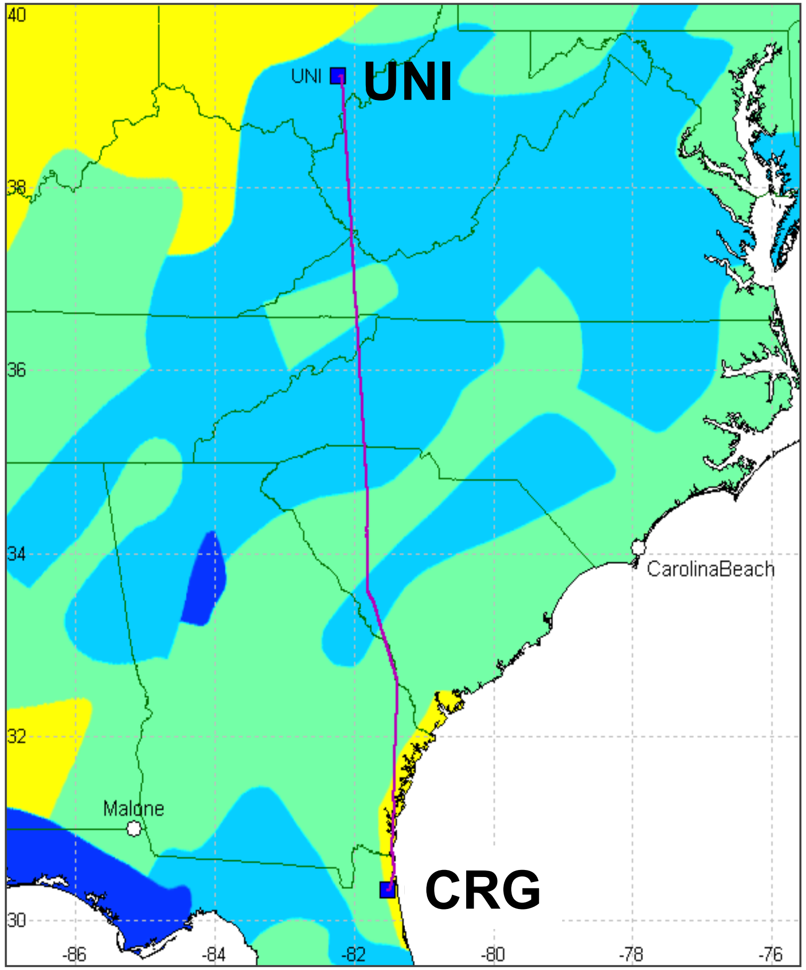
Flight 11 Results – Cape Race, Newfoundland

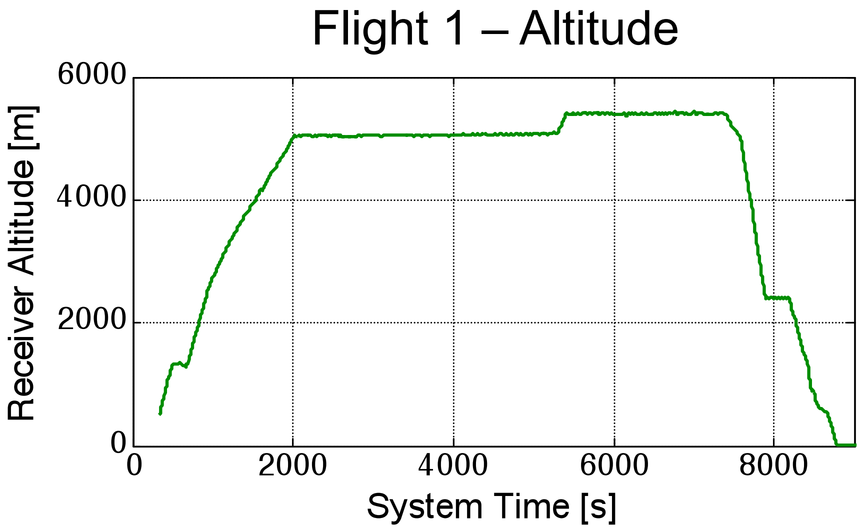


- Very long path from Xtm; large seawater part.
- Larger ASFs over land
- LPM predicts a peak at ~ 8500 from Nantucket Island, not matched by the TMS.
- Differences are ~ 0 to 0.4 μs



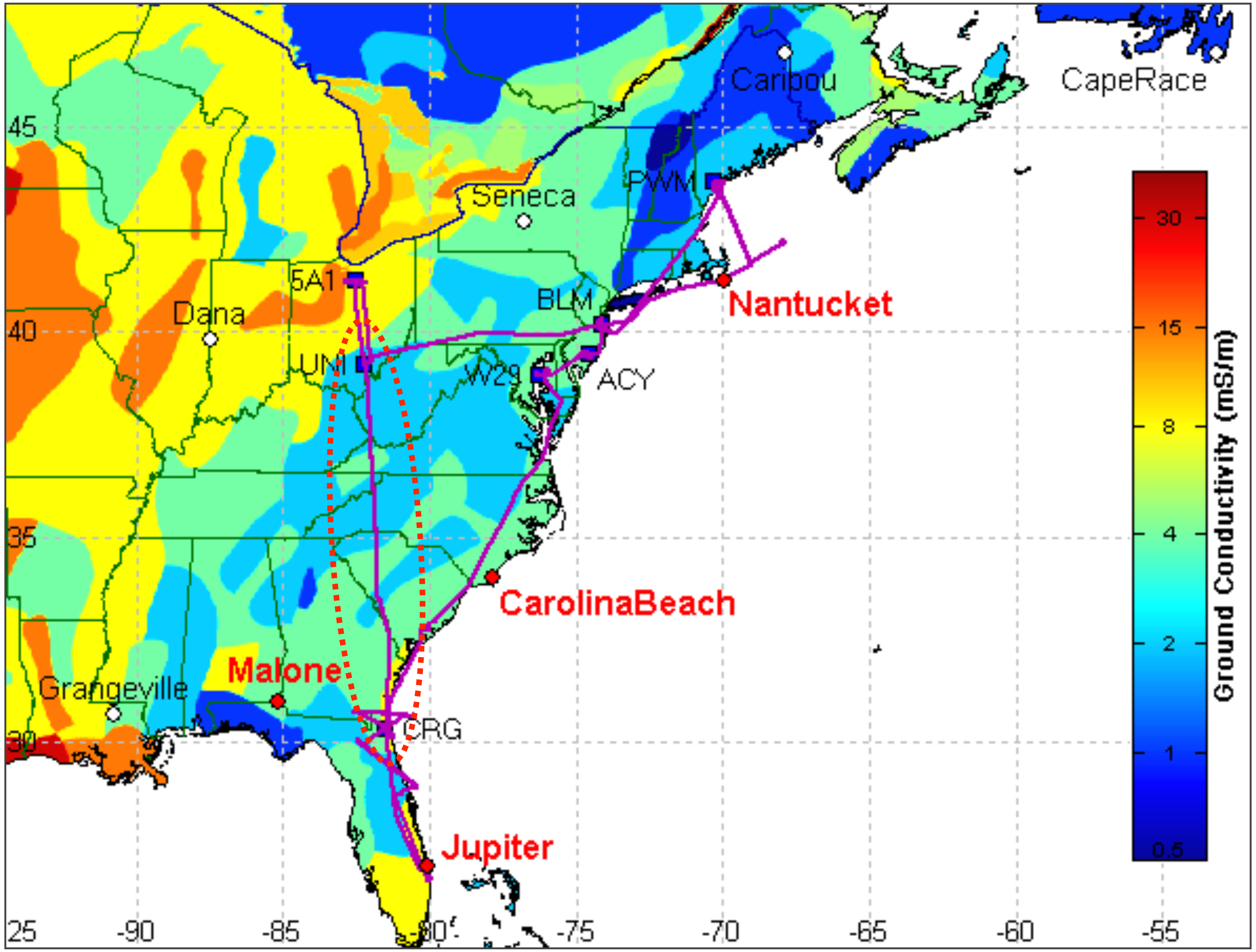
Flight 1 – Ohio University Airport (UNI) to Craig Municipal Airport (CRG)



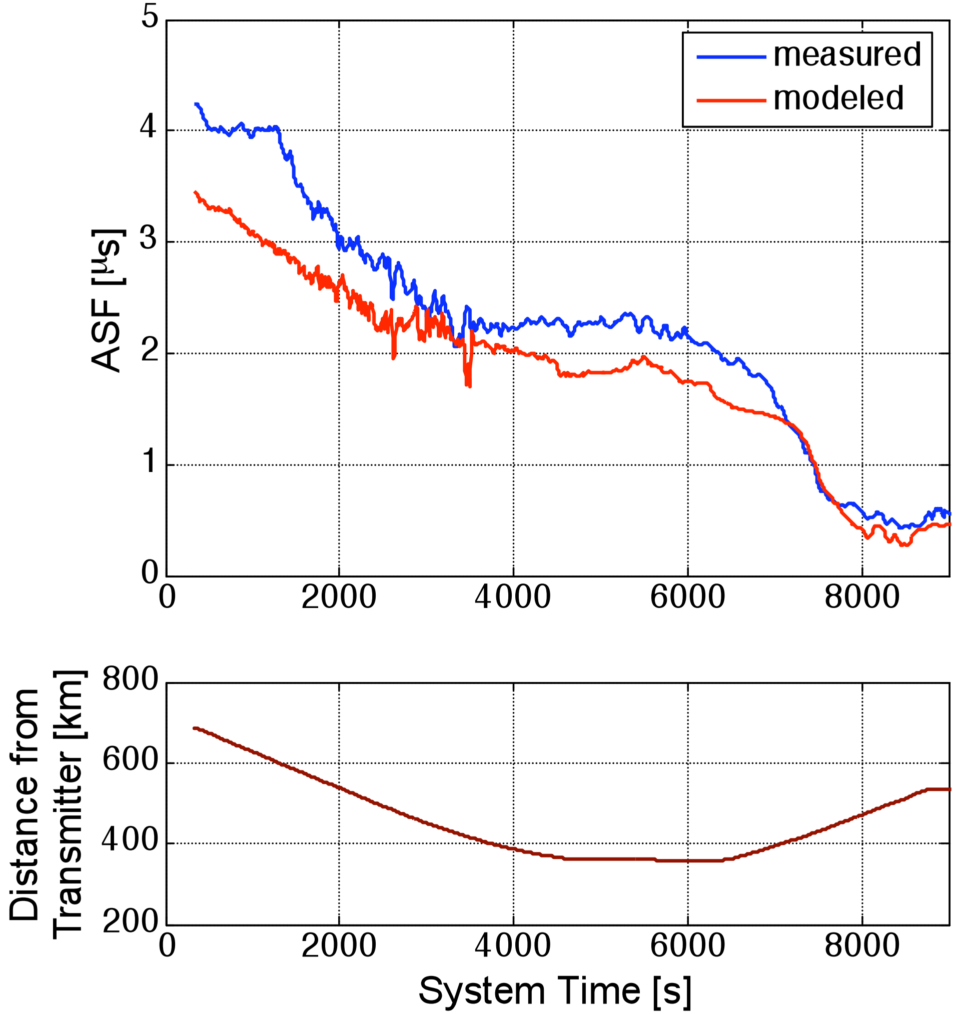


- Long flight over land
- Enroute altitude around 5000 m
- Low mountains for first half of flight

Flight 1 – **UNI to CRG to Loran Xtms**

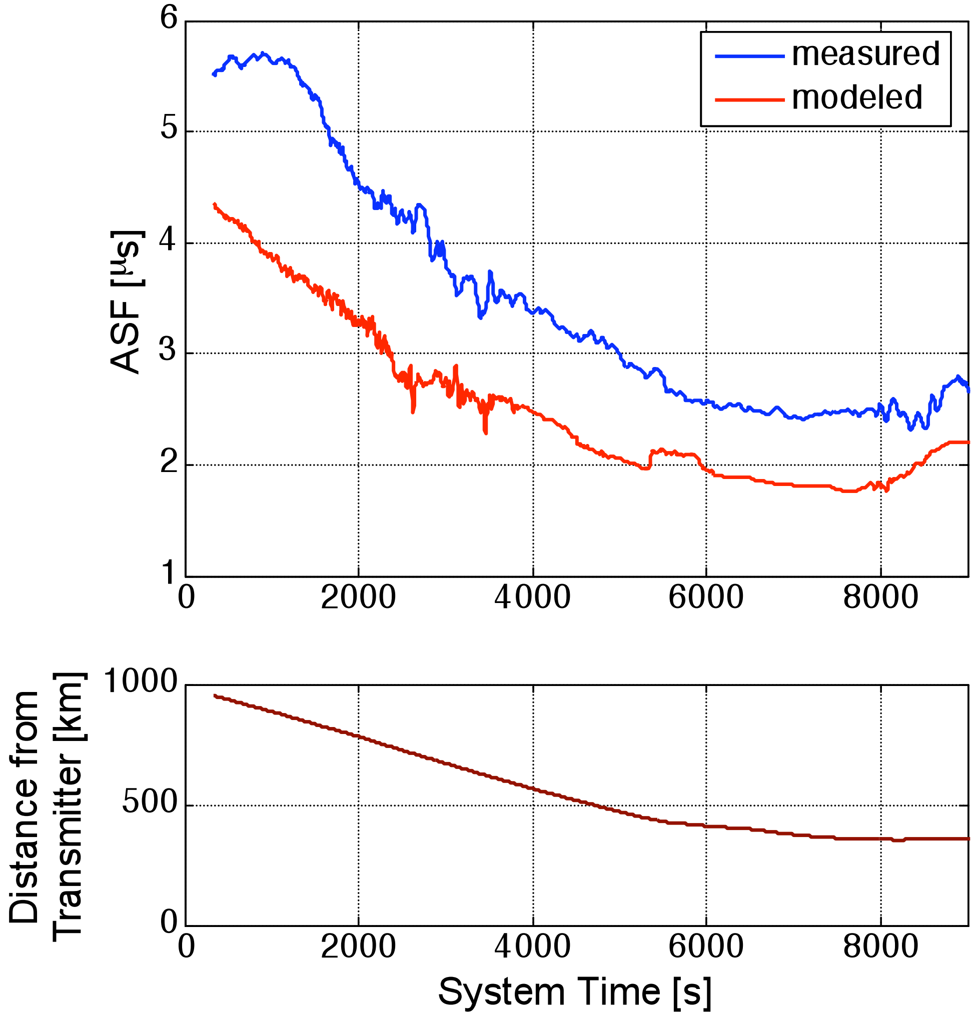


Flight 1 Results – Carolina Beach, NC



- Path from the Xtm is medium length.
- Path is all over land except near the end of the flight.
- Up to 1 μs offset when the distance over land is greatest (at beginning)
- Good match where there is a large seawater part (at the end)

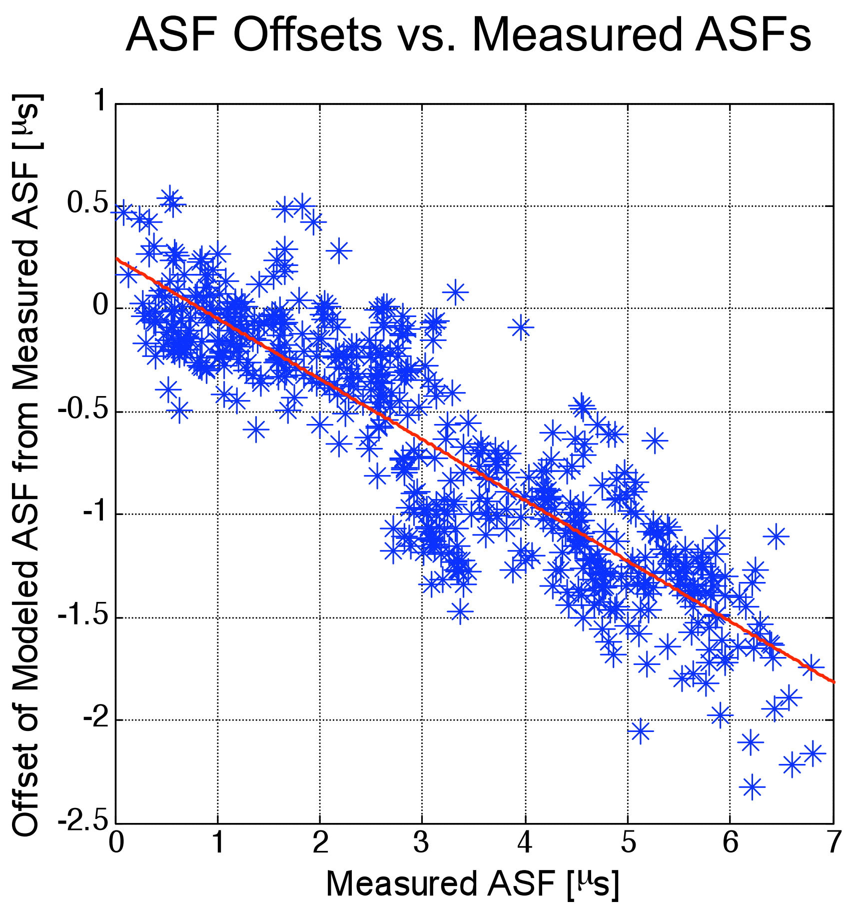
Flight 1 Results – Malone, FL



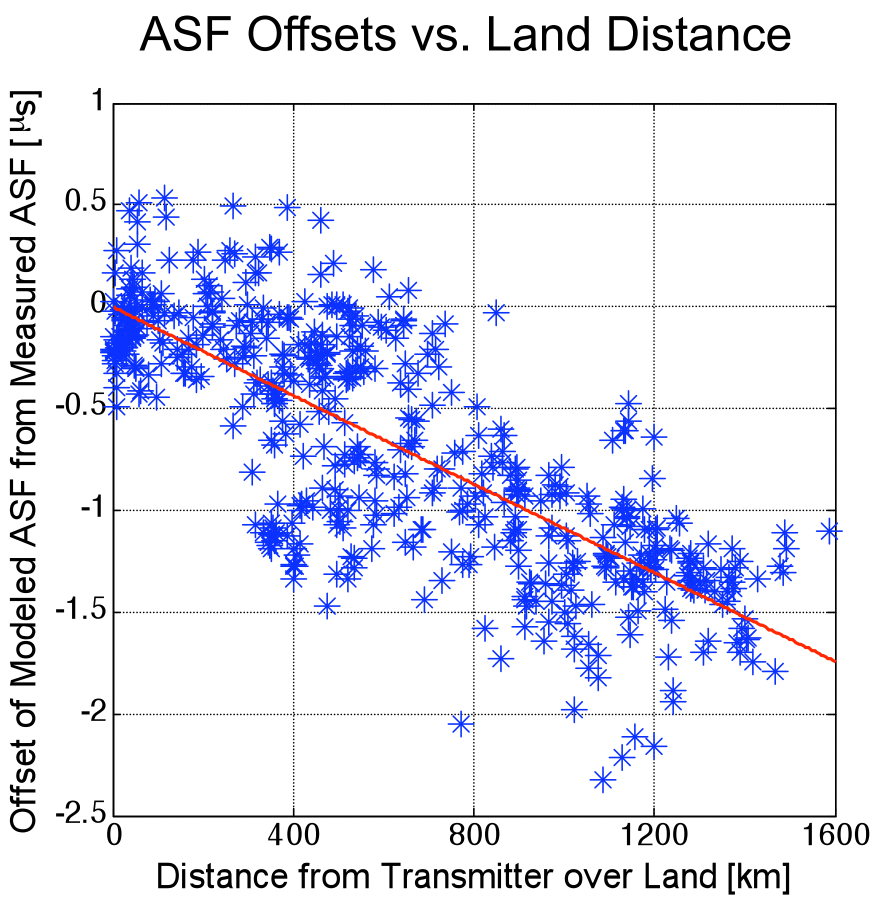
- The path from the Xtm is completely over land.
- The path is longest at the start and shortens as the flight progresses.
- Modeled ASFs follow the general trend of measured ASFs with:
  - offset of about 1.5 μs near the start
  - decreasing to about 0.6 μs near the end.

ASF Offset Bias

- Comparison of modeled and measured ASFs:
  - Good agreement when path from Xtm is short or mostly over seawater.
  - Modeled results always too low for a long, land path.
- All valid data points over the five days of data collection were aggregated.
- The modeled ASF falls increasingly below the measured ASF as the ASF becomes larger.



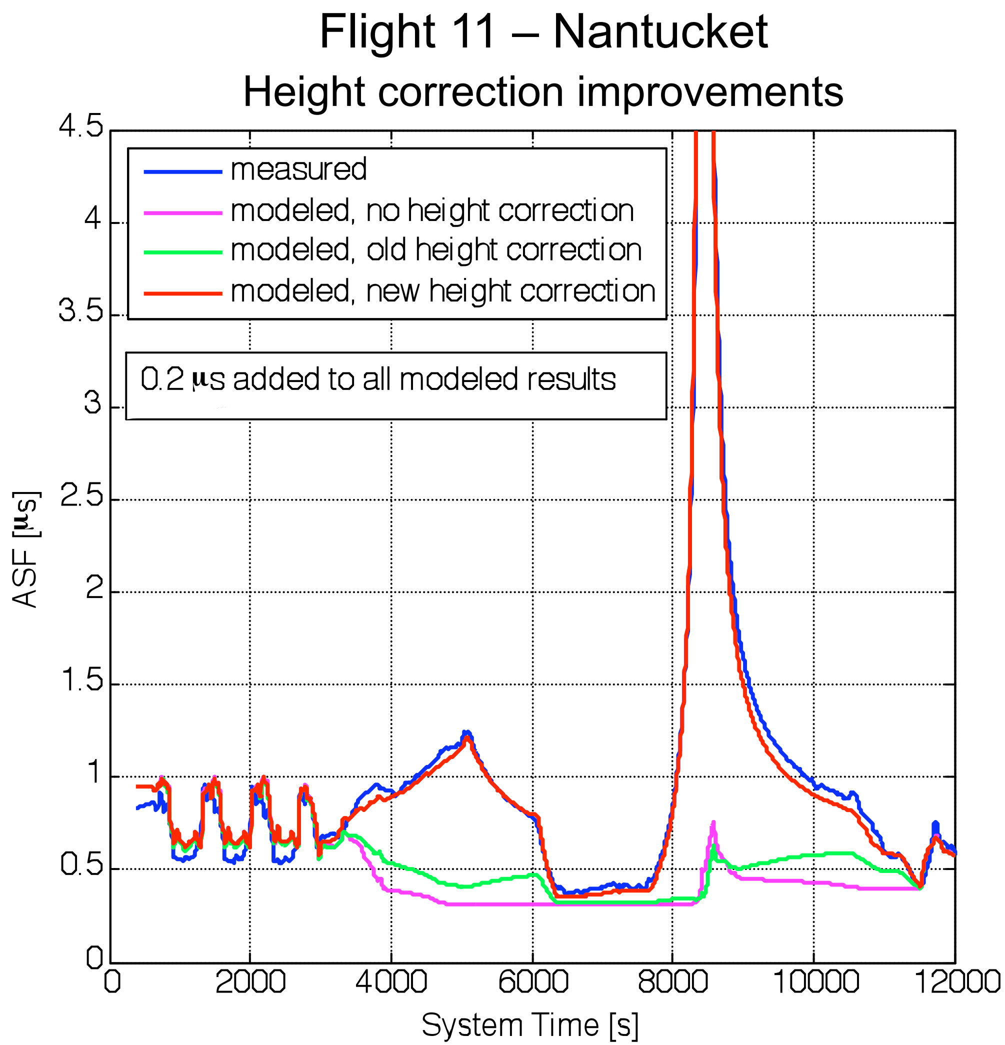
ASF Offset Bias, continued



- ASF offsets is related to distance over land.
- The slope of the line in this plot is 1.1 ns per km.
- Need to determine if bias is due to an error in the model, an error in the measurement system, or faulty external data.
- For example, bias can be removed by halving values obtained from the ground conductivity map.

Height Correction

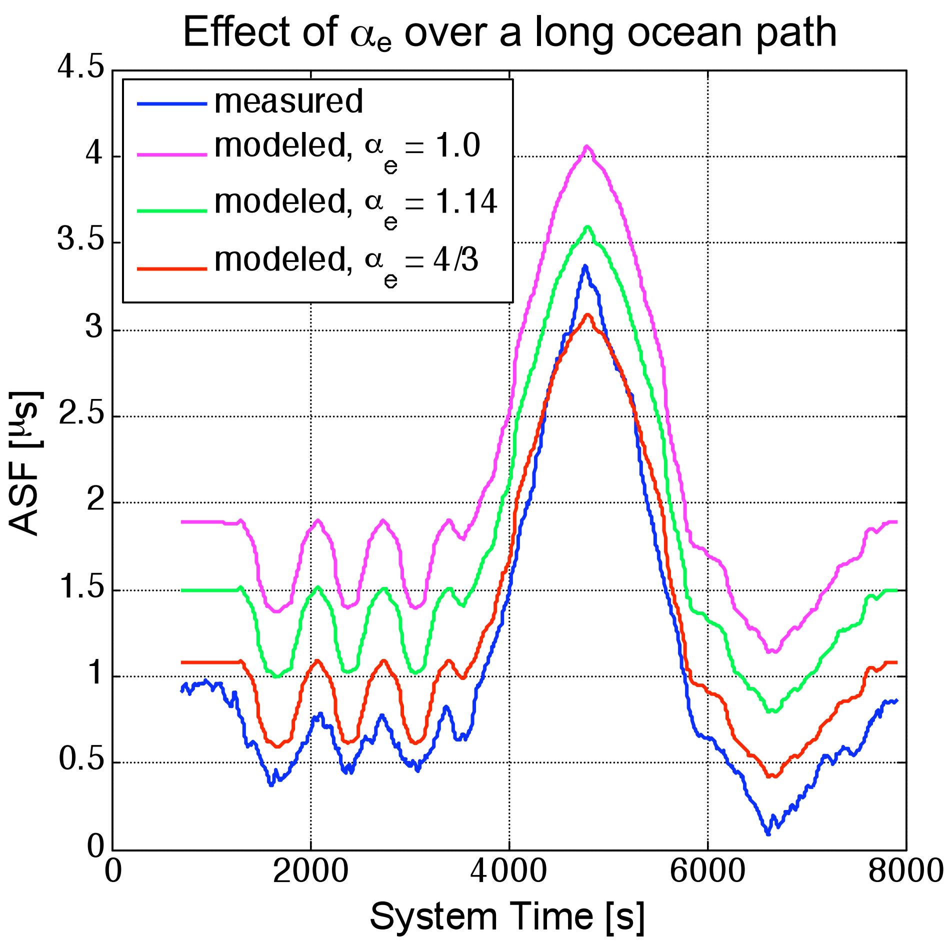
- A complex factor is used to correct for the altitude of the receiver.
- Correction is a function of distance, ground impedance, and altitude.
- Height correction was refined for better performance.
- While this correction may not be critical for navigation guidance, it is necessary for validation studies.



Effective Earth Radius Factor

- To compensate for atmospheric refraction, the actual earth radius, a, is often replaced by a larger value called the effective earth radius, a_e. Let $\alpha_e = a_e / a$.
- Traditionally, $\alpha_e = 4/3$ for medium frequencies, and 1.0 for very low frequencies.
- What is best for Loran?
- LPM has used 4/3 and 1.14 in the past.
- Examining the ASFs over a long seawater path such as the one shown here seems to indicate that α_e should be about 4/3 or even slightly higher.

Flight 4 – Nantucket



Summary of ASF "Errors"

- An "ASF offset bias," amounting to 1.1 ns per km of land path, or 1.1 μs for a 1000 km path. Should be able to detect cause and correct easily.
- After compensating for the offset bias, ~ 0.6 μs of residual error.
- Factors that contribute to ASF modeling errors:
  - Ground conductivity map is not very detailed or accurate.
  - Height correction could be improved.
  - Terrain slope correction could be improved.
- Note that system timing errors, measurement system errors, and temporal changes affect measured ASF but not modeled ASF, and thus are included in the observed "error".

Conclusions

- The Loran Propagation Model is efficient and robust, but requires additional validation and refinement.
- The TOA Measurement System produces precise and reproducible ASF measurements, but also requires additional validation.
- Comparing LPM and TMS ASF results revealed a offset bias. The cause needs to be identified.
- The remaining error, from all causes, is about 0.6 μs.
- Additional field testing and model refinement should bring the modeling error to less than 0.5 μs.

Acknowledgement

This work was supported by the Federal Aviation Administration, part of the United States Department of Transportation, under contract DTFA01-01-C-00071, Technical Task Directive 2.1: Loran-C Analysis and Support.

Questions?

<u>Additional Information:</u>

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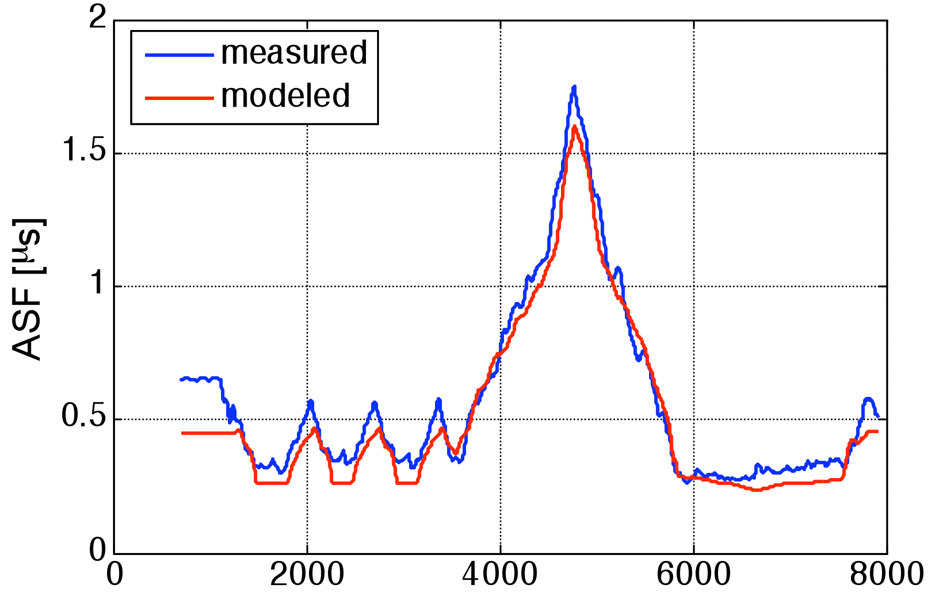
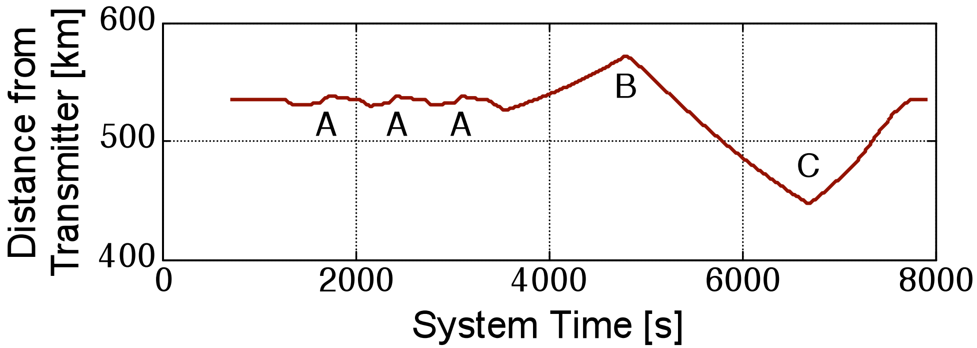
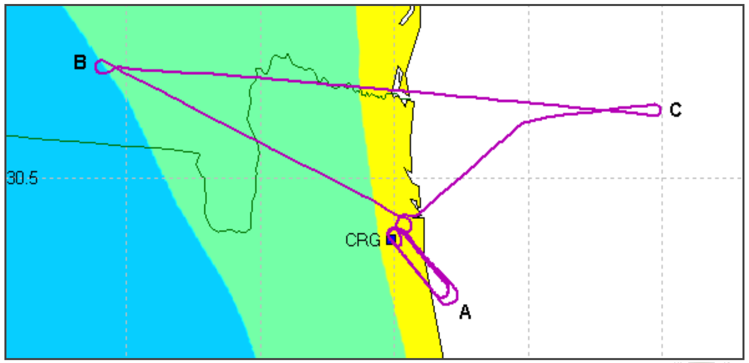
Additional Information

Flight 4 Results – Carolina Beach, NC

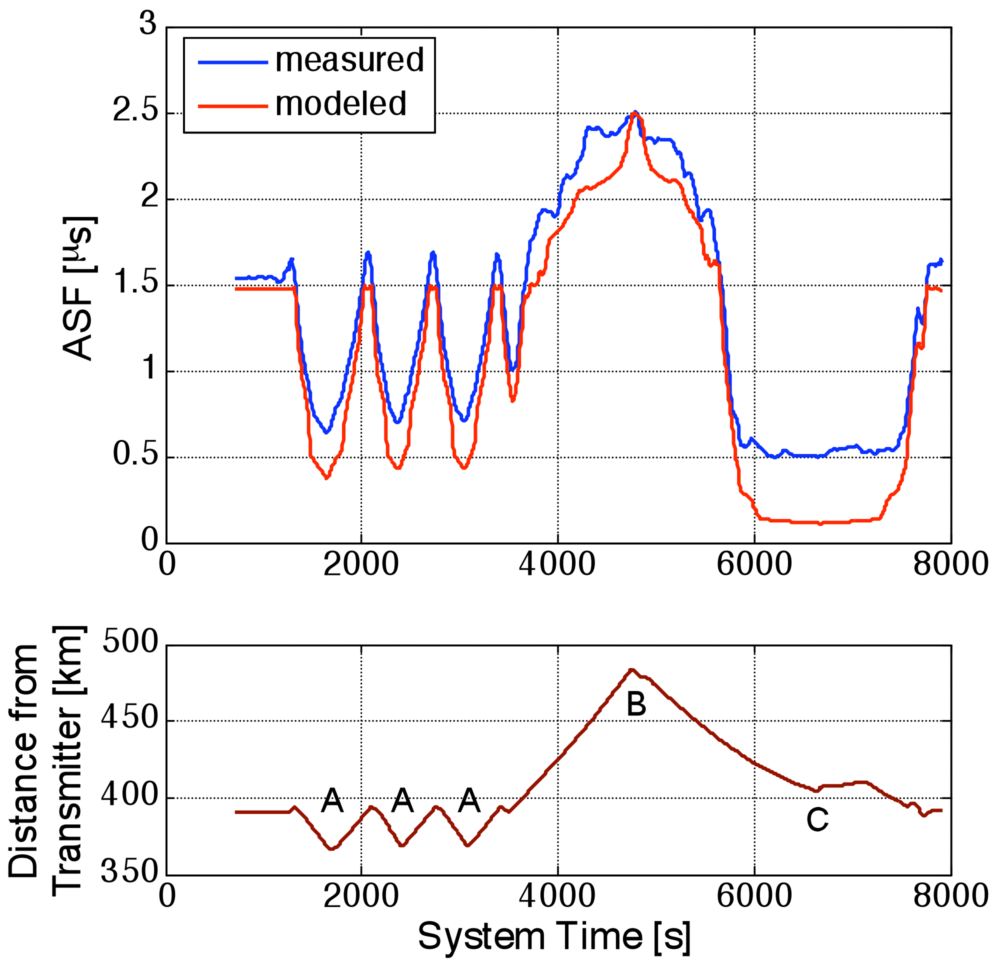




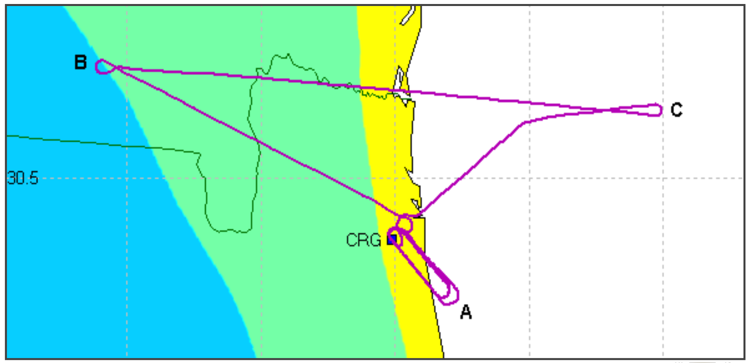
- Path from Xtm is relatively short, mostly seawater.
- Good overall match.
- Difference of 0 to 0.1 µs.
- Approaches at beginning
- Large central peak is due to going inland and back.
- Low ASFs over the ocean.



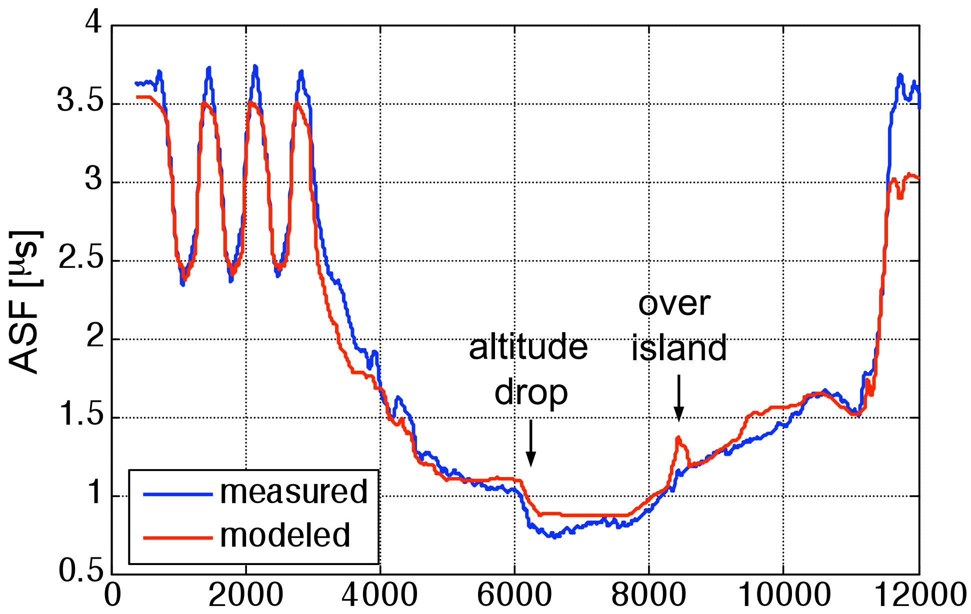
Flight 4 Results – Jupiter, FL

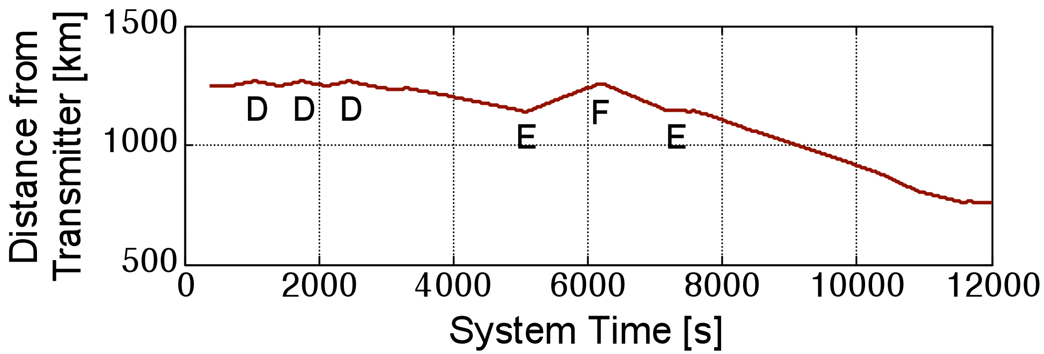


- Path from Xtm is relatively short, more over land than previous case.
- Low ASFs on right corresponds to largely seawater path.
- Differences are in the range of 0.2 to 0.3 μs.
- Other plot features are similar to previous case.

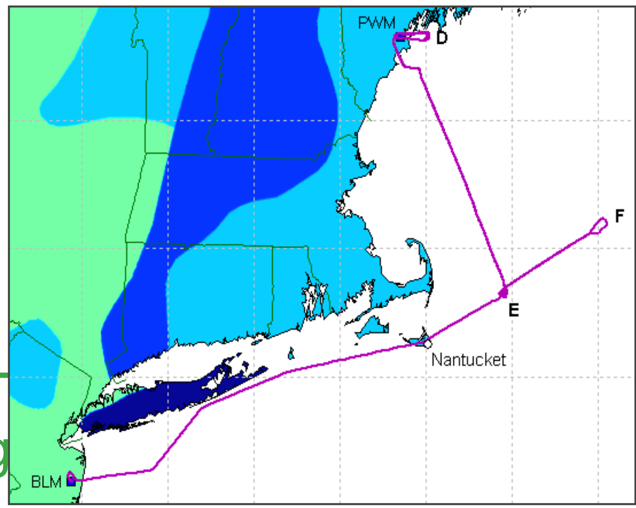


Flight 11 Results – Carolina Beach, NC

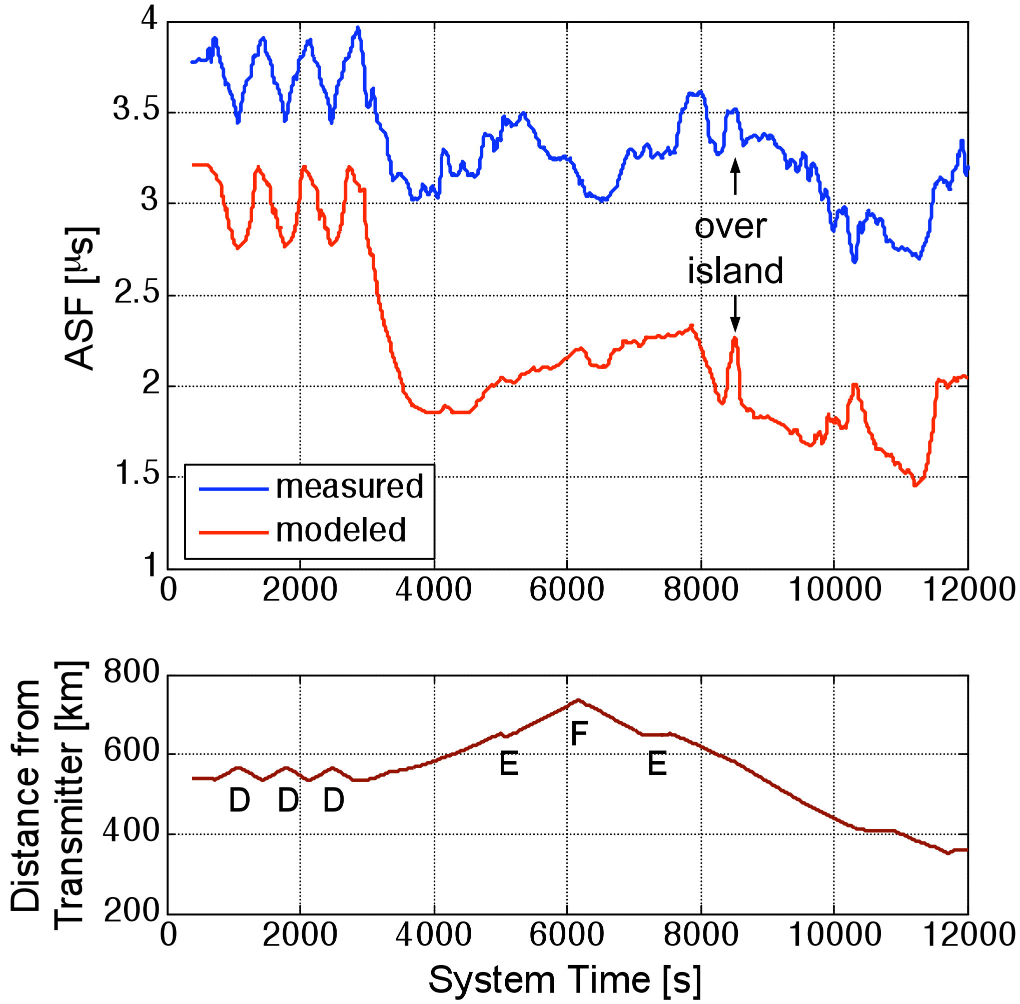




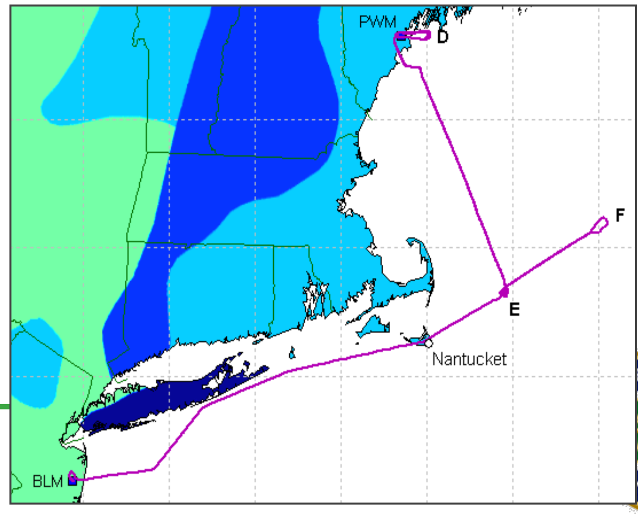
- Path from Xtm is fairly long with large seawater part.
- Three approaches on left.
- ASFs get lower over the seawater proportion
- Decrease in altitude seen at time 6000.
- The small peak ~ 8500 from Nantucket Island – not recorded by the TMS.
- Differences ~ 0.1 to 0.2 µs.



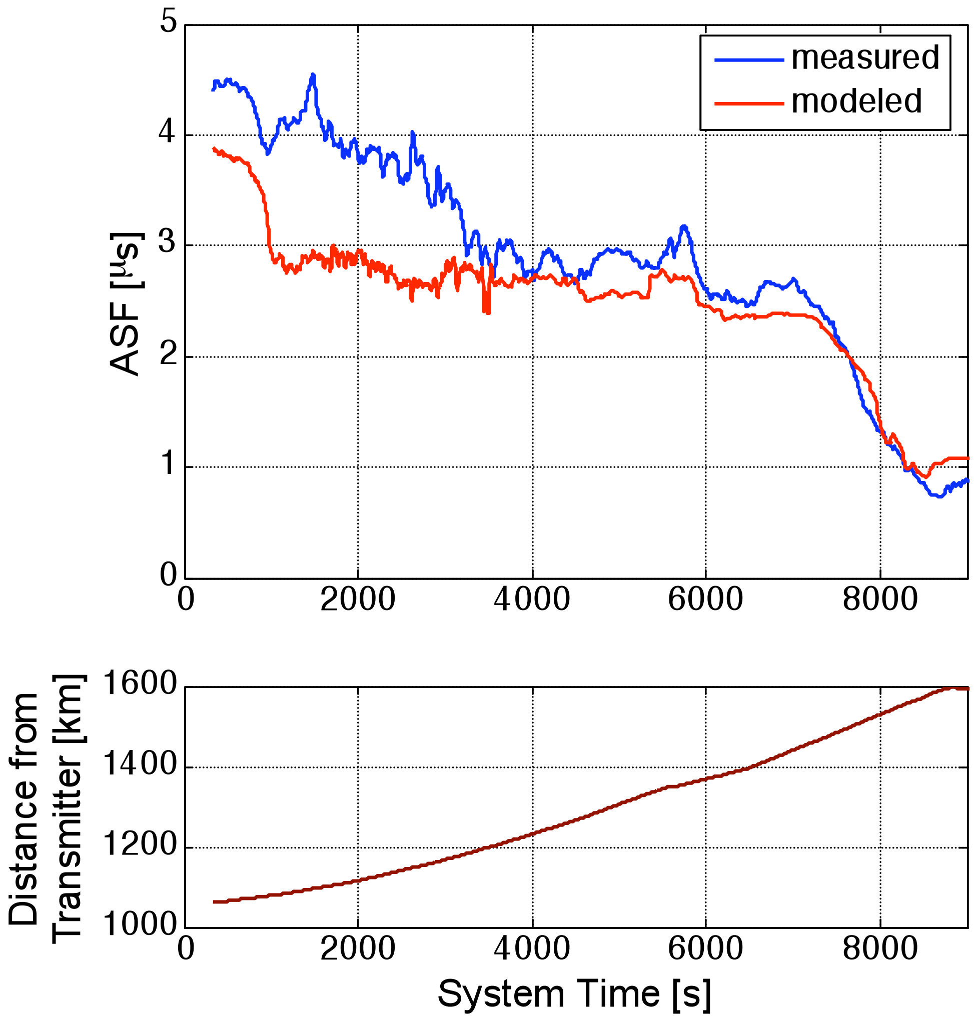
Flight 11 Results – Seneca, NY



- The path from Xtm is medium length, mostly over land.
- Measured and modeled ASFs have offset ~ 1 µs.
- Shape mismatches ~ 0.4 µs.
- TMS does register a small peak at time 8500, when the aircraft passes over Nantucket Island.

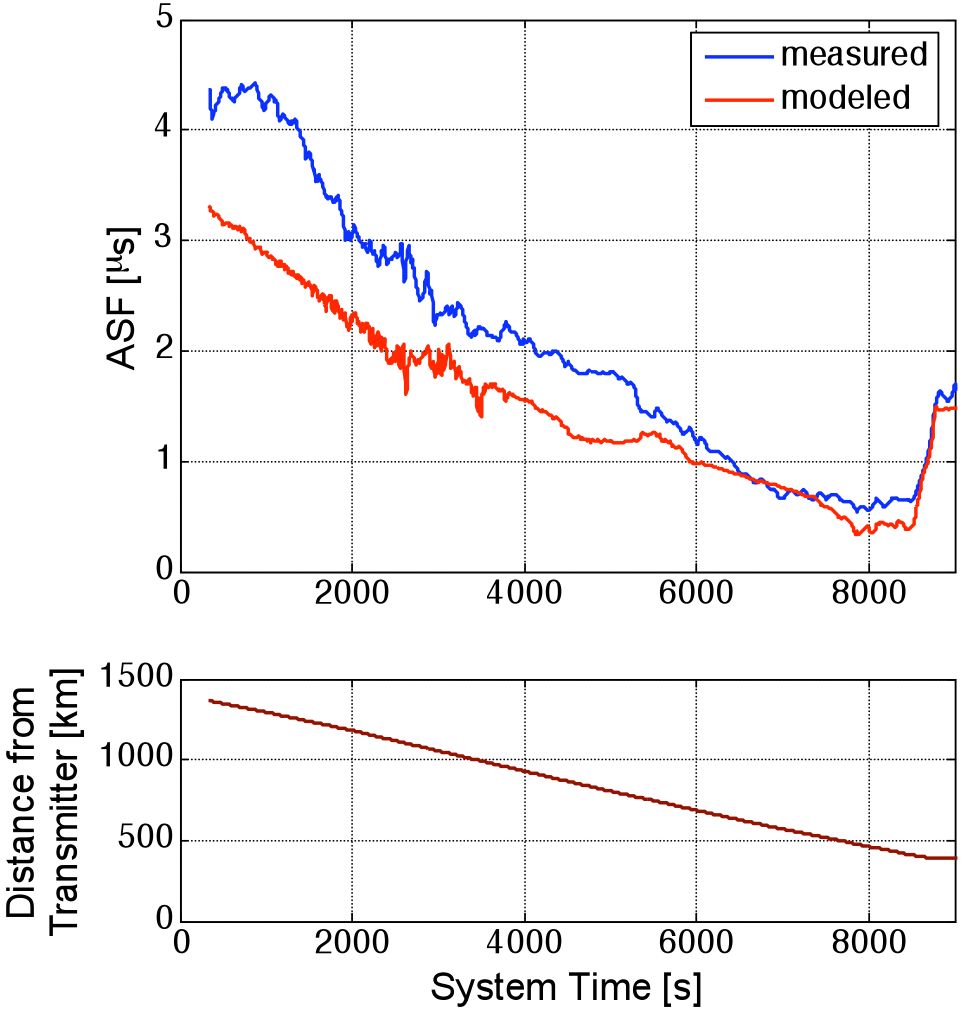


Flight 1 Results – Nantucket, MA



- The path from the Xtm is fairly long but partly over seawater.
- As the flight progresses, the path length increases, but the land component decreases.
- Differences are near 1 μs for the first third of the flight, but in the range of 0.1 to 0.2 μs for the rest.

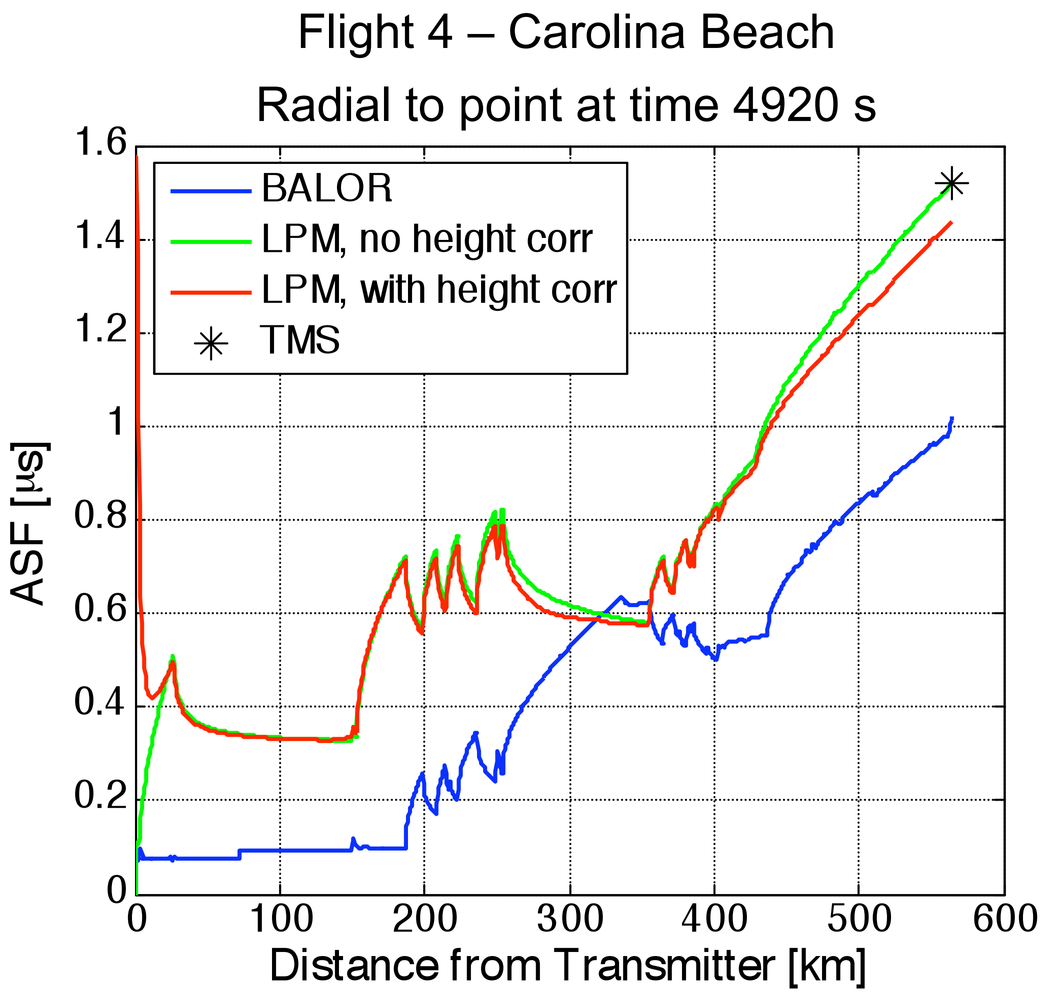
Flight 1 Results – Jupiter, FL



- The length of the path from the Xtm decreases steadily over the course of the flight.
- The path is mostly over land.
- Measured and modeled ASF results show an offset of approximately 1.4 μs near the start, decreasing to 0.2 μs near the end.

Supplement 1a

- Comparison of results from BALOR version 3.0 and current LPM beta version.
- The plot shows modeled results along a radial to a single test point.
- This radial skims the coastline at times.
- Some of the differences between BALOR and LPM are due to the different coastline databases used.



Supplement 1b

- Again, the plot shows the modeled results along a radial to a single test point.
- In this case, we are dealing with a long radial over land.
- The "noise" is due to mountainous terrain.
- The ASF measured by the TMS is considerably higher than the prediction from either model.