D1.17A VDES Channel Model
Satellite Channel Characteristics

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VDES Channel Model Development

- New analysis results for VHF ship to satellite channel
  - Description of exactEarth AIS dataset and collection parameters
  - Signal power characteristics
  - Distribution of samples by elevation angle
  - Signal power (loss) profile by elevation angle (large scale)
  - Comparison to free space loss
  - Small scale variations and statistical fading model
  - Channel stability over short term
  - Summary and Follow-up Planned/possible activities
- Further questions regarding Tapped Delay Line channel model presented at the Cape Town intersessional meeting?

Satellite Channel Model
The eE dataset

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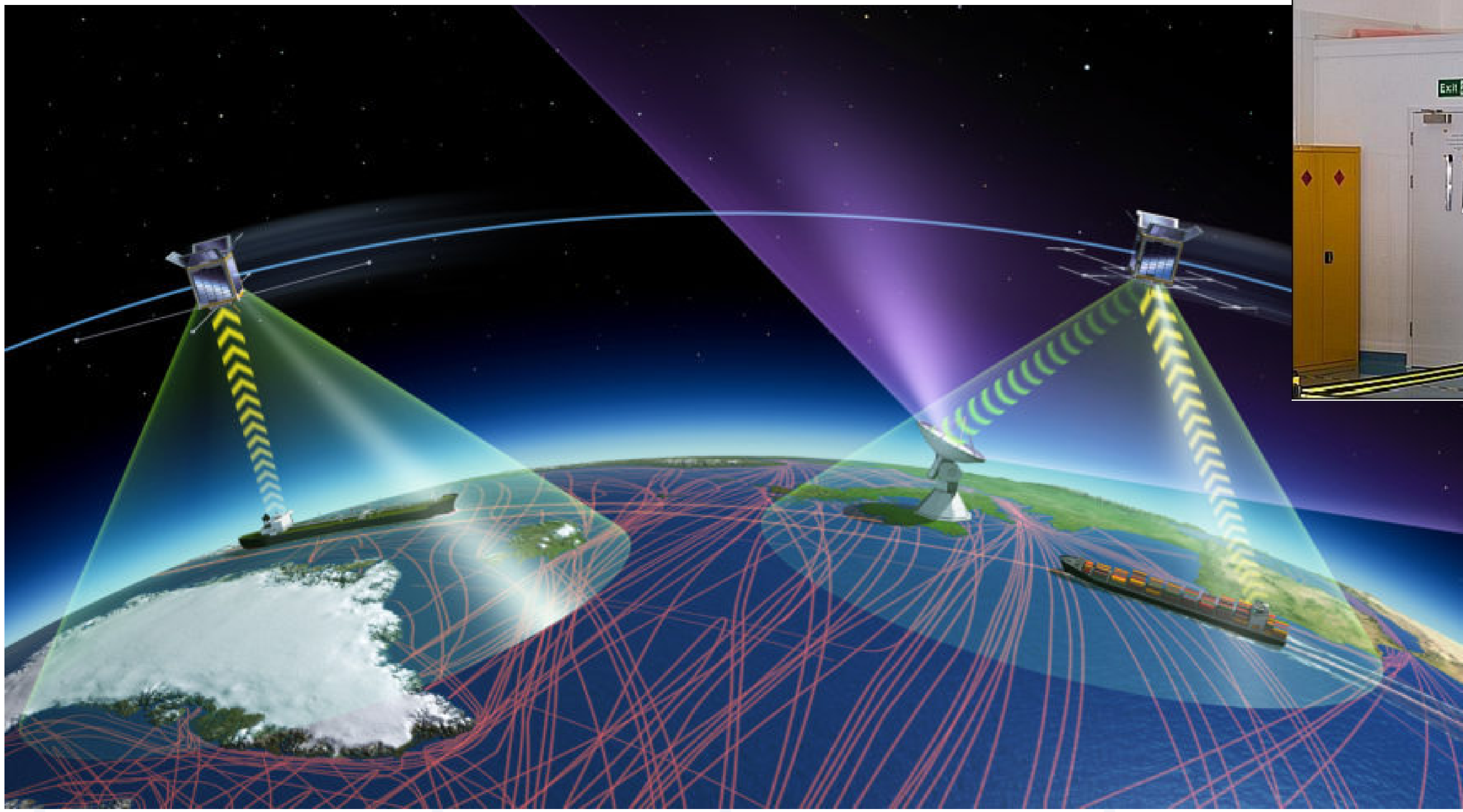
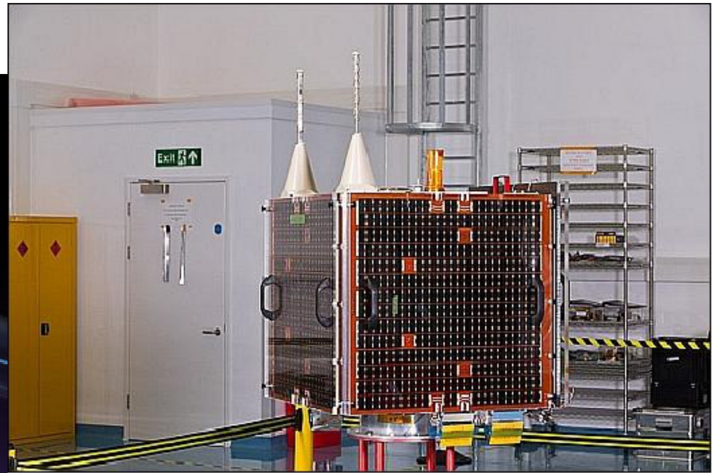
- In early 2017 exactEarth provided IALA with a record of satellite AIS signal detection statistics over a period of approximately 1 day in a low vessel density region (21 Jan. 2017, low density regions, Pacific and Indian Oceans)
- The data was collected and aggregated in a such a way to provide the ability to assess the small and large scale signal power variations that occur on the ship to satellite VHF data link
- Some of the characteristics of the data:
  - Used one of exactEarth's high detection performance satellites at an altitude of approximately 817 km (circular, polar orbit)
  - Data collected on AIS channel 1 and 2 (most is from a single channel only, 1,234 files were 2 chan.)
  - A wide range of MMSIs with both high and low terrestrial reporting rates (3, 6, 10 seconds)
  - Full passes of detection data from the lowest possible elevation to as high as the satellite appeared for that vessel on that pass
  - Power and elevation statistics were provided for each ships and satellite pass in a single file
  - There were 9,578 such files and 1,703 unique MMSIs
  - A total of 221,853 individual power, elevation, range measurements for these vessels

Satellite Channel Model
The eE satellite data collection

LEO Satellites orbit the earth approx. every 100 min

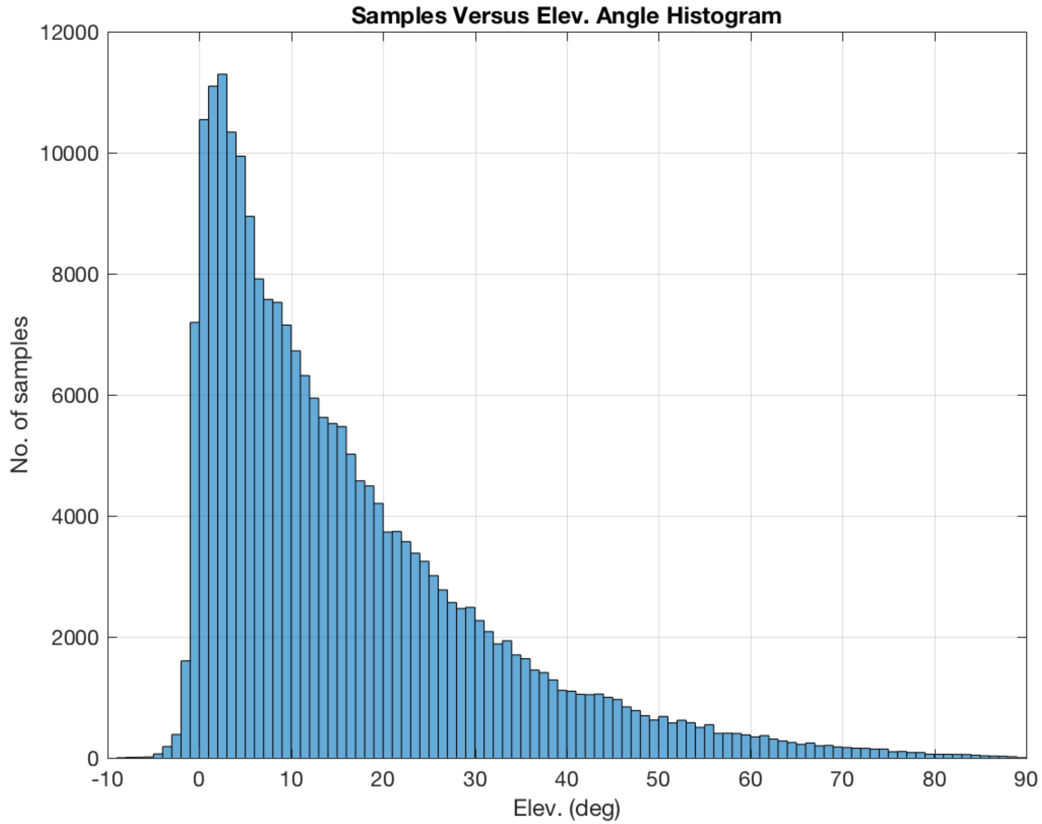




https://directory.eoportal.org/web/eoportal/satellite-missions/e/ev-1
http://spacenews.com/wp-content/uploads/2016/05/AIS-ESA-879x485.jpg

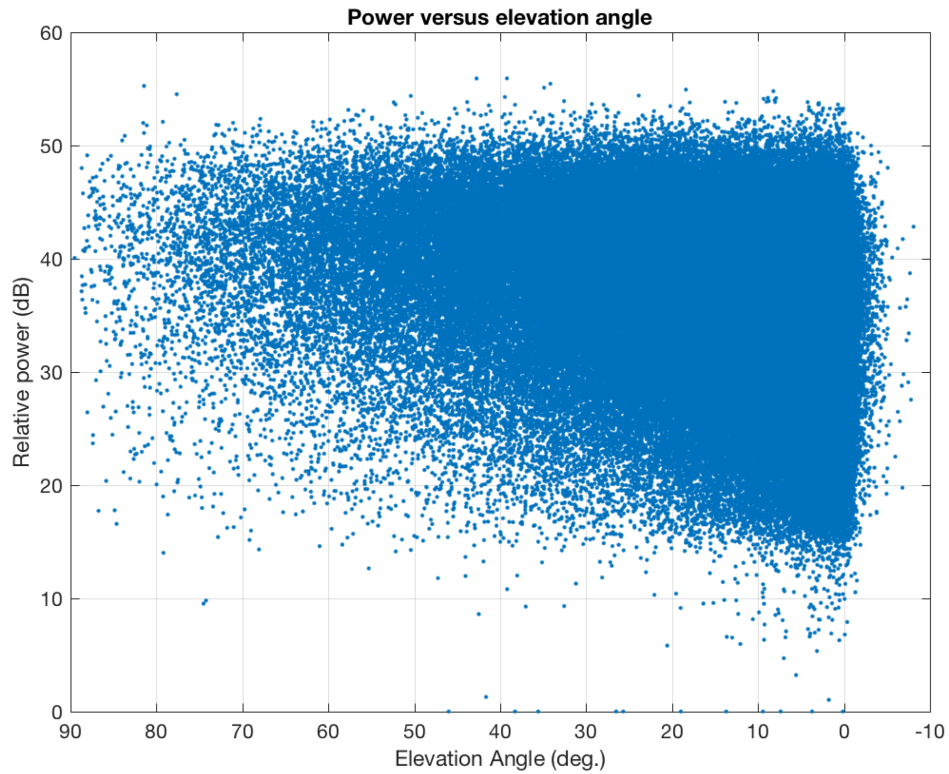
Satellite Channel Model
The eE dataset

- Some statistical characteristics of the dataset:
  - For low earth polar orbit, all areas of the earth are covered, however for any given user on the earth's surface, most of the time the satellite is at a low elevation angle
  - This is because the relative speed of the satellite with respect to the ship is substantially lower when the satellite is near the horizon
  - If detection were equal at all elevation angles, we expect the number of messages received to have this same distribution – and that is about what we see here
  - The good detection at very low elevation angels is surprising!



Satellite Channel Model
The eE dataset

- Satellite signal levels
  - Signals received by the eE satellite cover a wide range of signal levels
    - Power range > 50 dB!
  - The distribution appears wider at the lower elevation angles, but this is due to the much higher number of samples received at low elevation angles (see previous page)
  - Due to strong fading, a sliding window was applied to power measurements for each pass over elevation to extract either running maximum or median signal levels
  - These results were then averaged over elevation angle for all passes to reveal the power level trend over angle (see next page)



Note: The data received was not adjusted to actual power levels, however the sensitivity of eE satellites is very high, putting the lower end of the distribution well below AIS standard -118 dBm level (assume -123 dBm).
This will make the stronger signals approx. -80 dBm at the sat receiver.

Satellite Channel Model
Large Scale Effects

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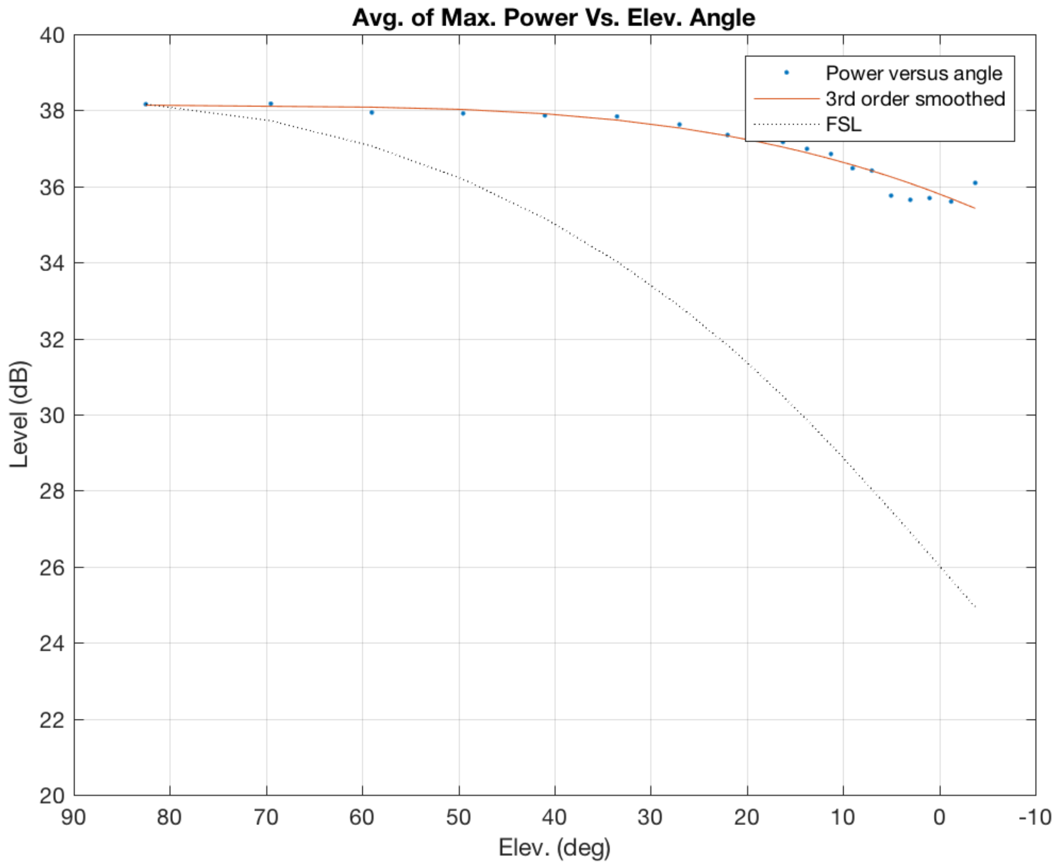
Theoretical Expectation?

- Free space path loss variation from nadir (below satellite) to the edge of coverage (earth's limb) is expected to be about 11 dB, with closest signals being the strongest (dashed line)
- Note that the ship antenna radiation pattern is roughly opposite to this, with strongest gain to the horizon (some patterns are shown in VDES standard document)
- *How much do these compensate for each other?* Ans. – quite a bit!
- Overall variation near to far is less than 2 dB based on max. sig. levels,



Note: FSL at 90º is ~135 dB, so a 12.5 W ship into a 7 dBi to horizon ant., 2 dB losses, omni sat, should have level of 46 dBm – 135 dB = -89 dBm
Estimated max. sig. level is approx. -80 dBm – as we would expect!

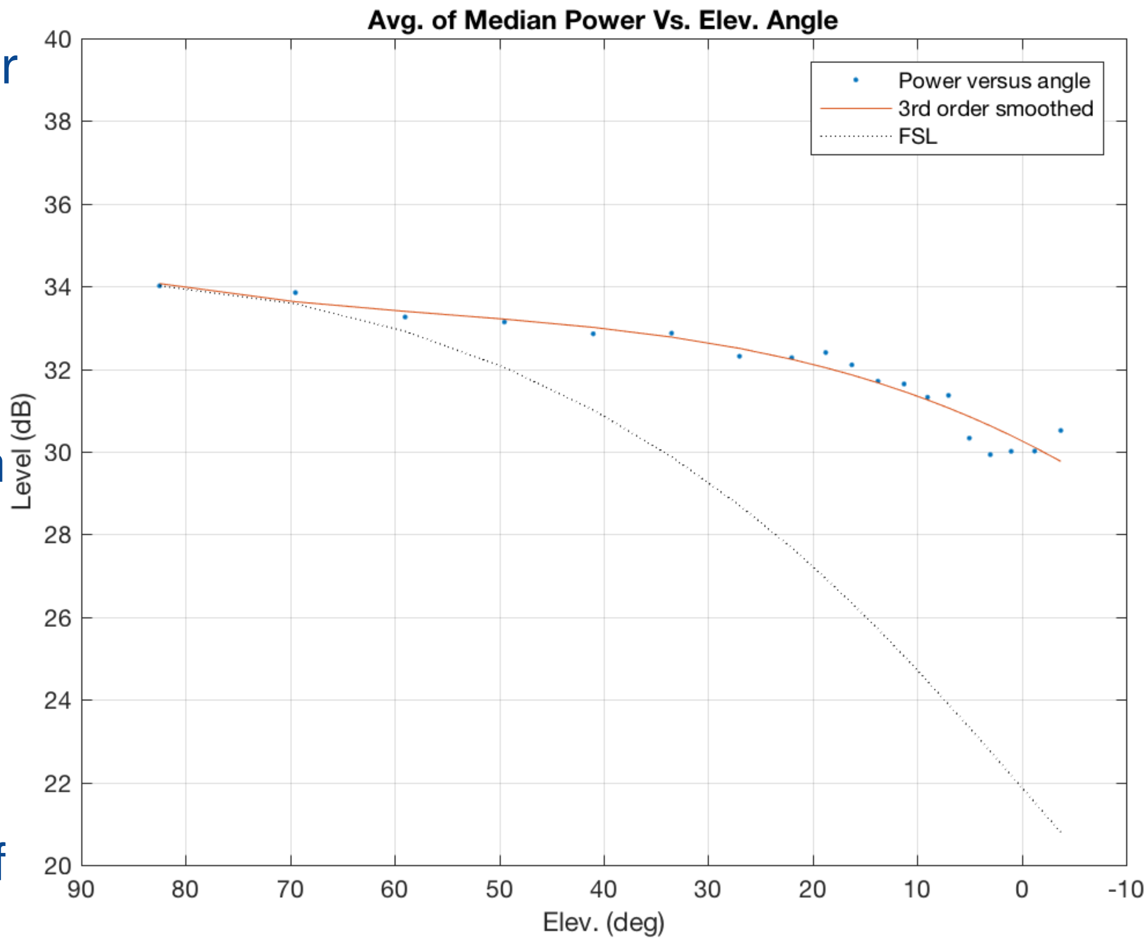
Satellite Channel Model
Large Scale Effects

What about 'median' signal levels?

- The total path loss variation from near to far (90º elev. to 0º) is only about 4 dB using median levels

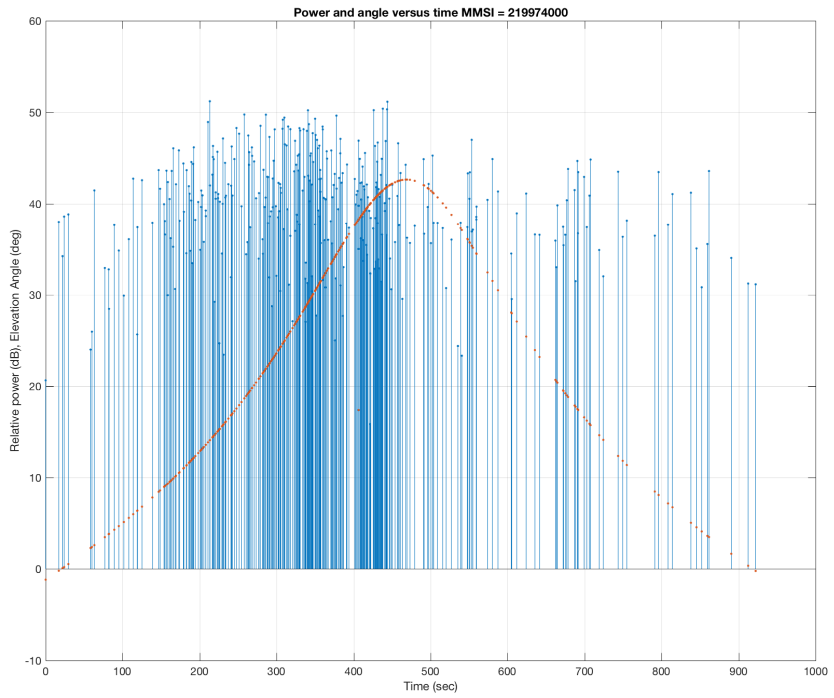
(& overall median levels are about 4 dB below rolling elev. window maximums)

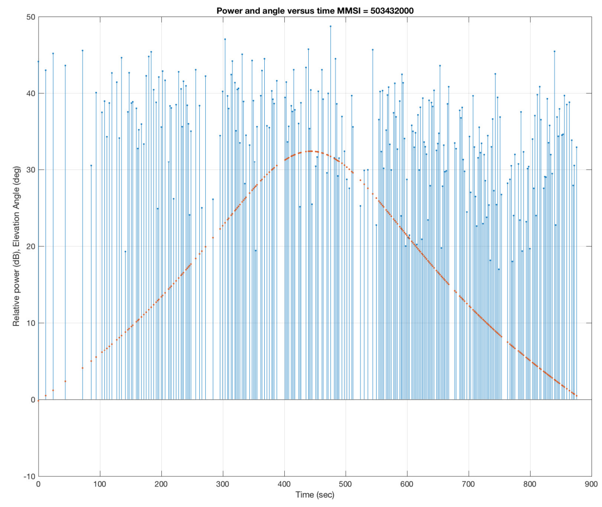
- The median levels are the power midpoints on a particular 'pass' within the specified angular window range
- 4 dB variation is 7 dB less than expected based on free space path loss variation (dashed line)
- An interesting phenomenon is the flattening of loss and even reversal of loss beyond the horizon!



Satellite Channel Model
The eE dataset

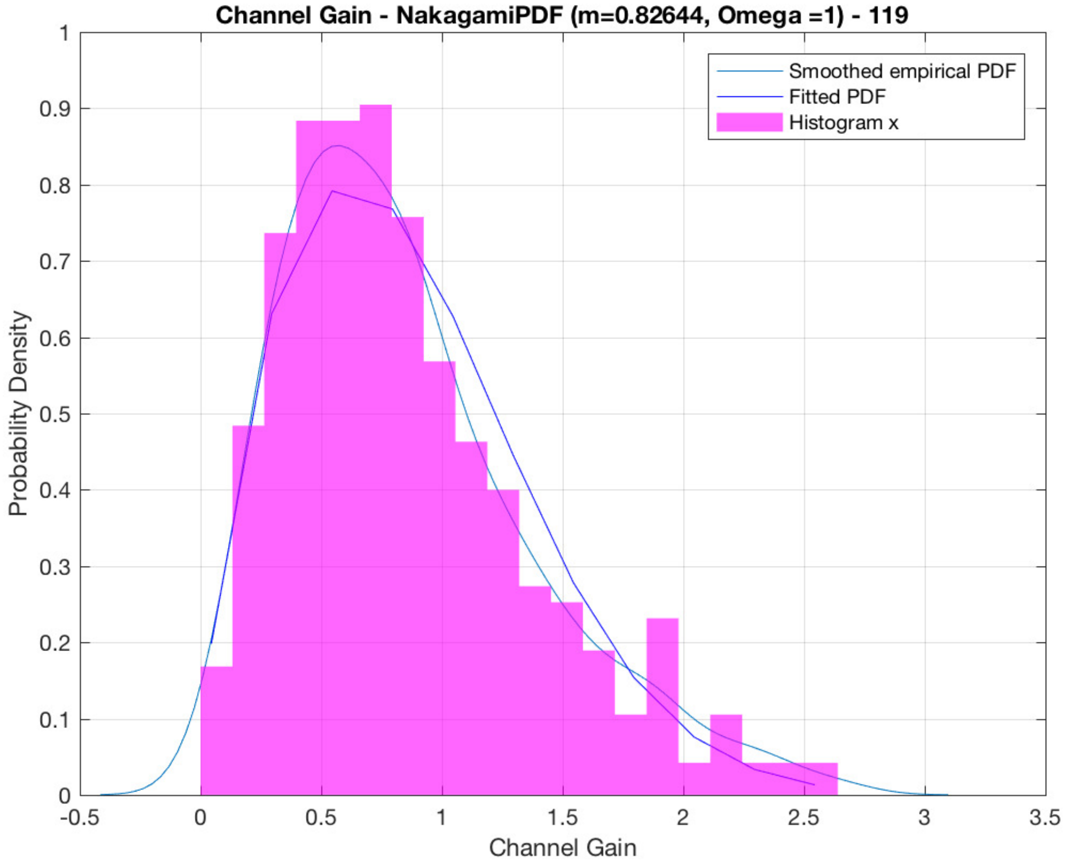
- A detailed look at 1 ship over 1 pass
  - The graphs show power versus time for a single ship and satellite pass
  - The satellite elevation angle (in degrees) for each power reading is also provided
  - Each stem is a received message power reading (in dB units)
  - The power does not vary substantially with changing elevation angle, but changes relatively rapidly over time, and over a 20+ dB range – i.e. presence of fast fading
  - *What type of distribution is this?*





Satellite Channel Model
Statistical Fading Model

- Many different distributions were investigated for fit to data, and the Nakagami distribution was a good fit in almost all cases for full and partial ‘passes’ for each vessel
- Fading information is ‘in the tails’, so fit at extreme low values is very important
- The PDF fit is shown as a solid line, with real-data level histogram in solid bars



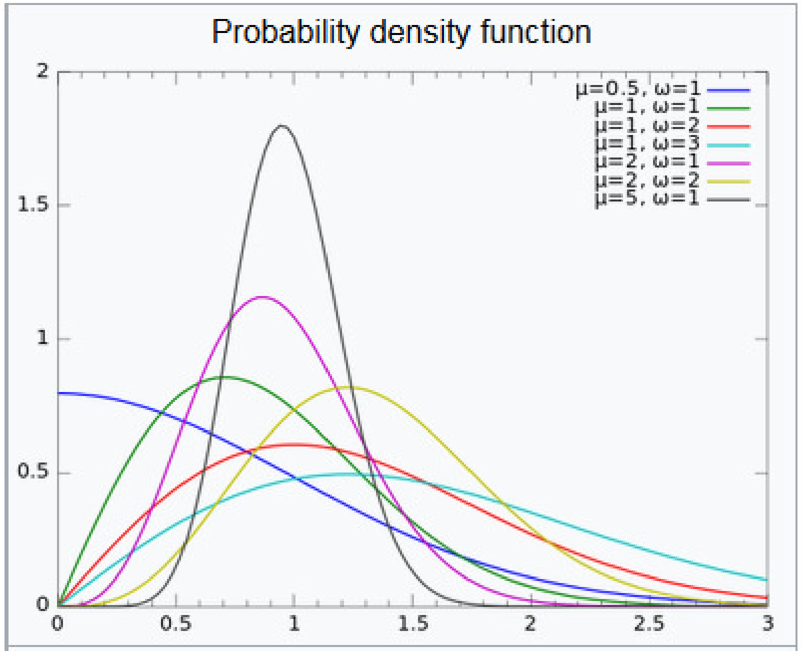
This pass is a Nakagami, *m*=0.83 distribution, 2nd pass was *m*=0.68

Satellite Channel Model

Statistical Fading Model – What is the Nakagami Distribution?

- The Nakagami probability distribution is provided by expression below
- The distribution suits signal envelope characteristics for a high multipath environment
- If 2nd param omega is normalized, *m* specifies the shape
- For *m*<1 the signal has wider spread than a Rayleigh dist'n
- *m*>1 has lower spread than Rayleigh distribution

Nakagami

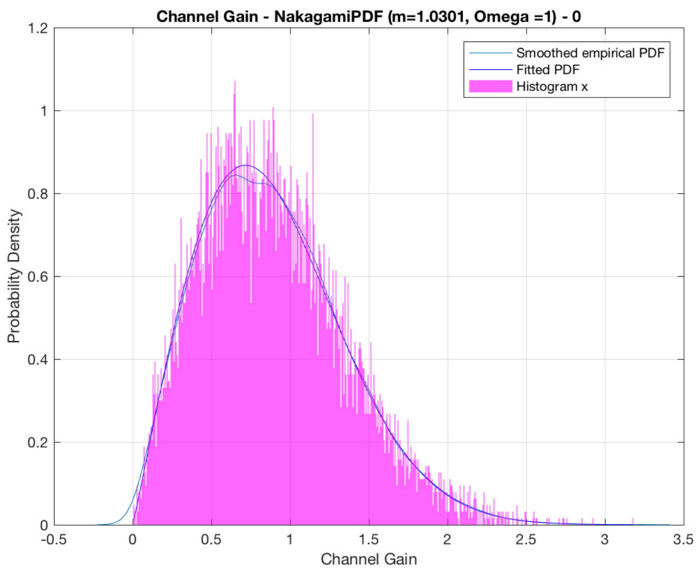


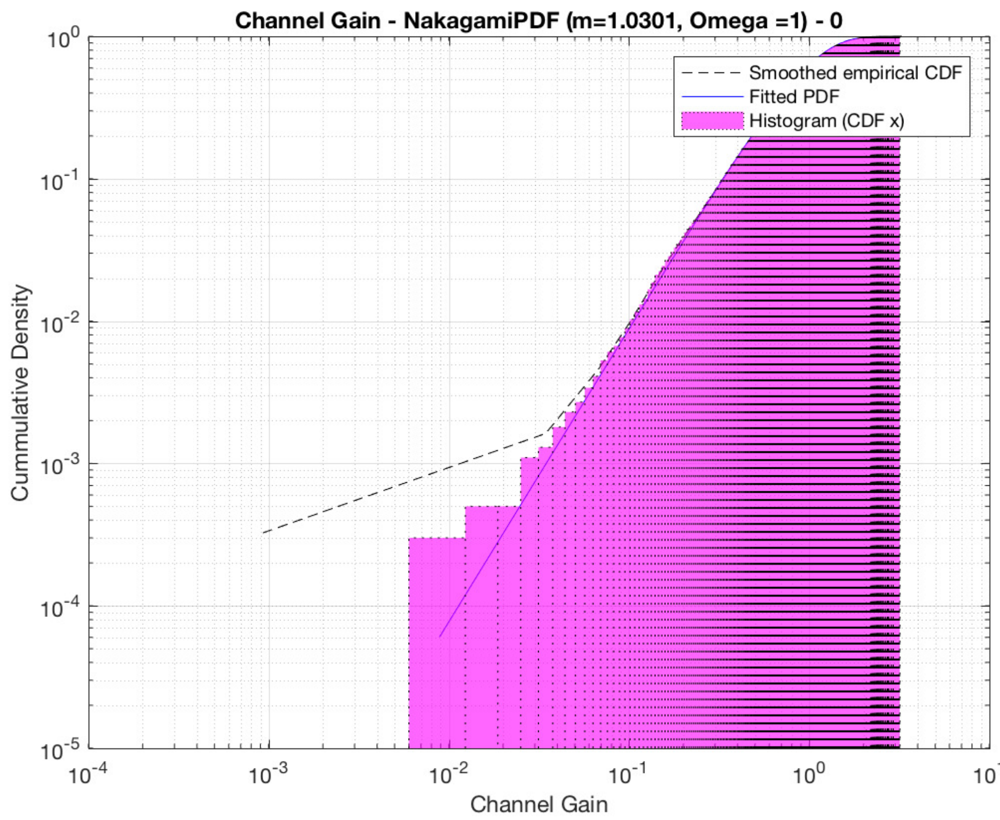
$$f(x;\,m,\Omega) = \frac{2m^m}{\Gamma(m)\Omega^m}x^{2m-1}\exp\left(-\frac{m}{\Omega}x^2\right), \forall x \geq 0. \;\; (m \geq 1/2, \text{ and } \Omega > 0)$$

https://en.wikipedia.org/wiki/Nakagami_distribution

Satellite Channel Model
Statistical Fading Model - Nakagami

- A special case is the Nakagami distribution is for *m*=1
- This is exactly the Rayleigh distribution
- Curve fit and PDF and CDF for simulated Rayleigh shown (note: fit value is very close)

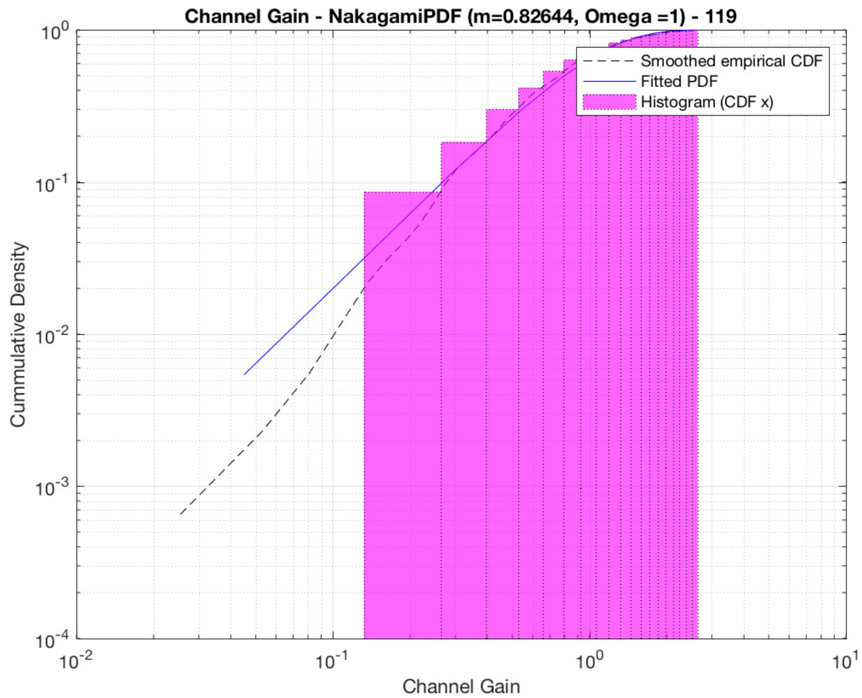


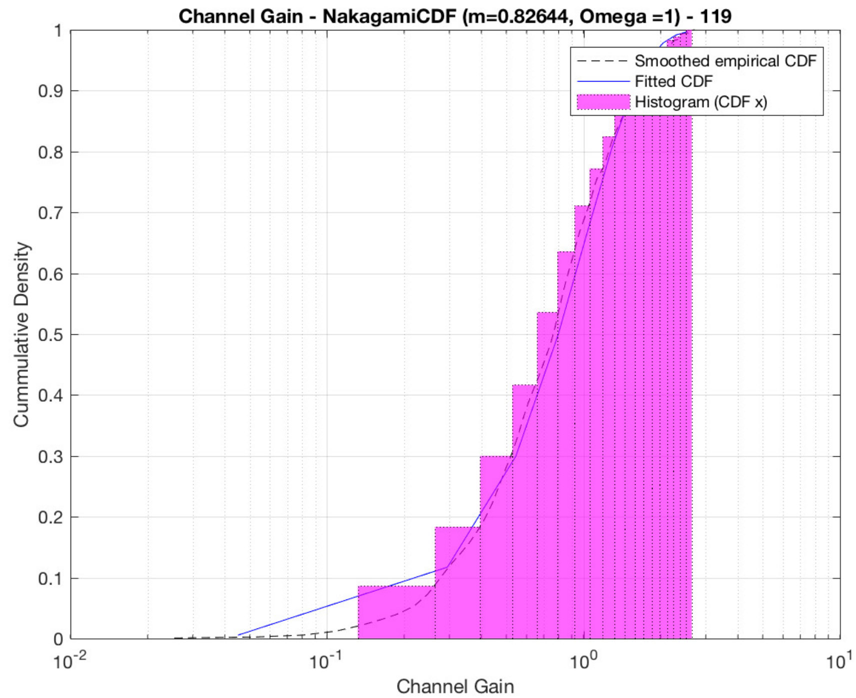


Note: gain of 10^{-1} is equiv. to -20 dB power (or amplitude)

Satellite Channel Model
Statistical Fading Model

Same satellite data as before on log scale to show detail in lower 'tail' and the CDF

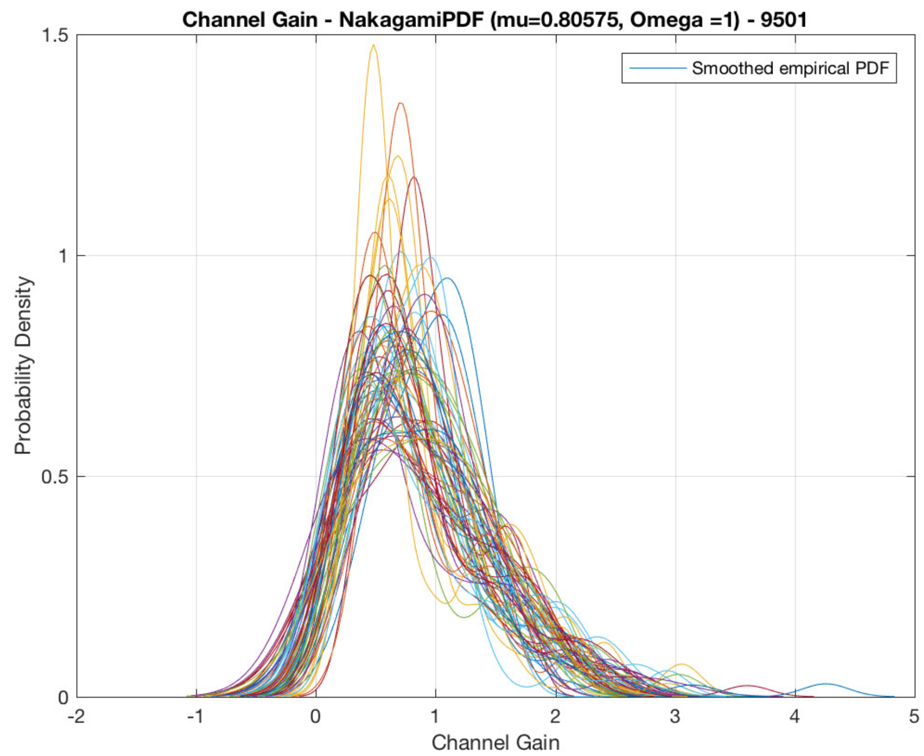




Note: gain of 10^{-1} is equiv. to -20 dB power (or amplitude)

Satellite Channel Model
Statistical Fading Model

- The figure at right shows about 50 of the smoothed probability distributions
- Note: negative channel gain (waveform envelope) is an artifact of the curve fitting routine, actual PDF values do not go below zero, mu value for last distribution only



Satellite Channel Model
Statistical Fading Model

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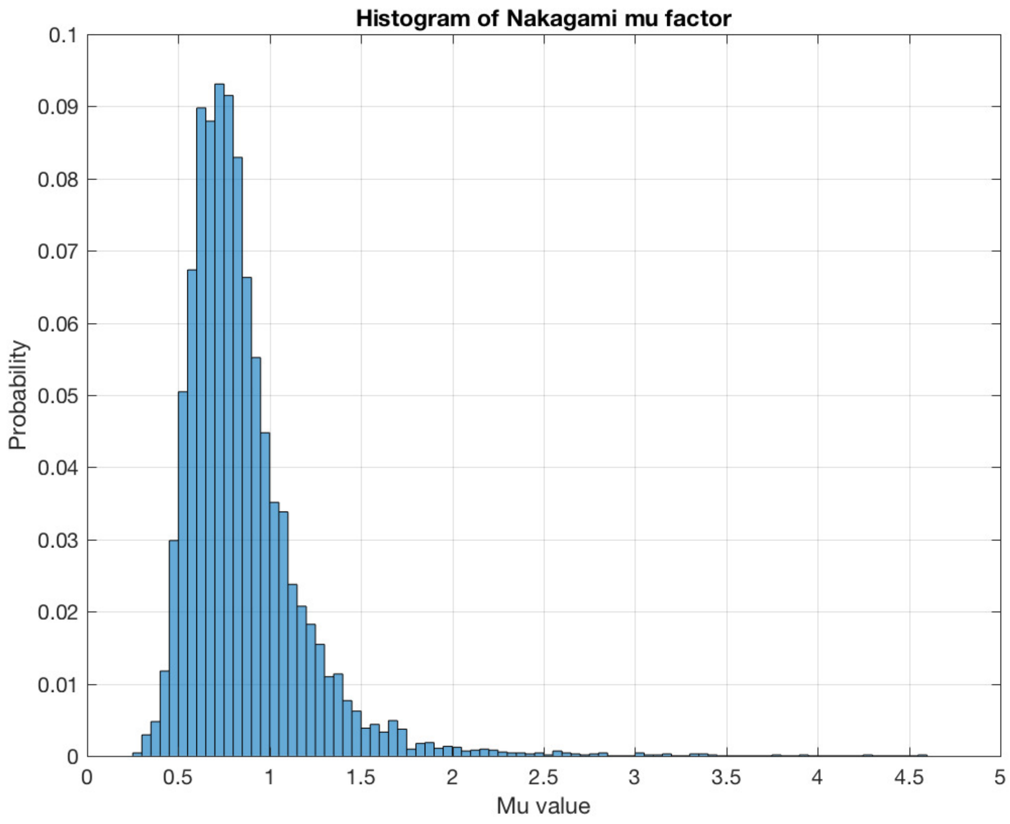
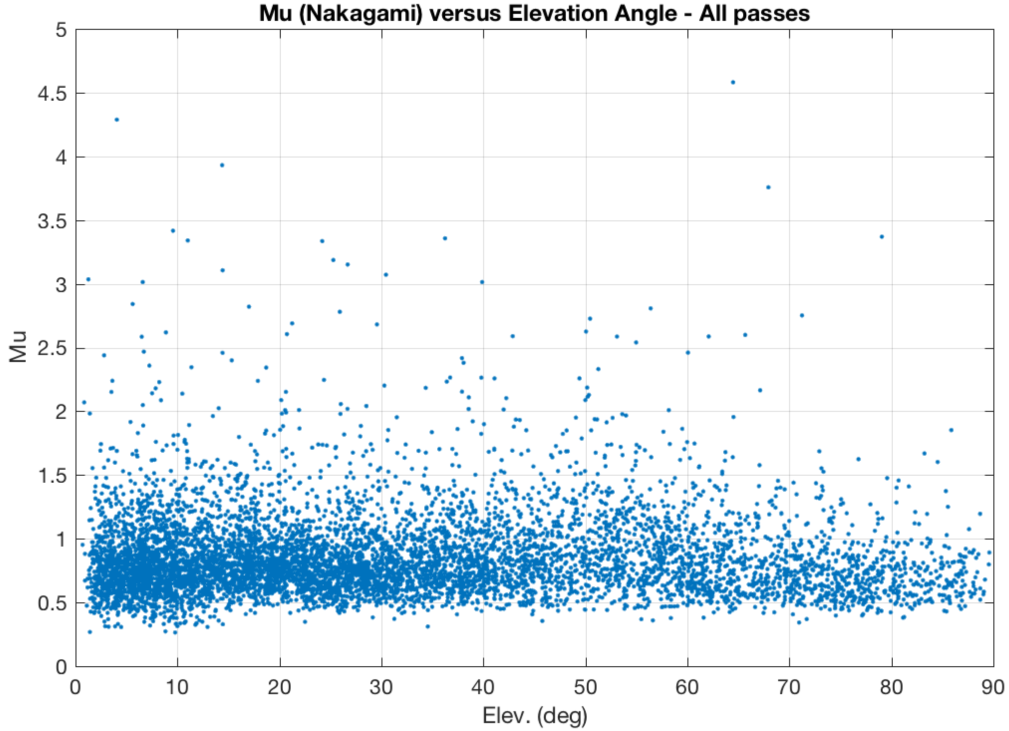
- Testing all of the nearly 10,000 satellite passes did not provide a very wide spread of *m* values, generally around 0.6 to about 1.5 (see next slide)
- The average was $m = 0.85$
- The probability distribution of all points analyzed is shown on the figure to the right



Satellite Channel Model
Statistical Fading Model

- The *m*-value of the Nakagami statistical distribution does not change substantially with elevation angle
- The *m*-value also does not change with vessel maximum power or average reporting interval
- Value does not change if shorter segments of passes are considered (say 2-5 minutes)
- These factors make the use of the average *m*-factor statistically valid

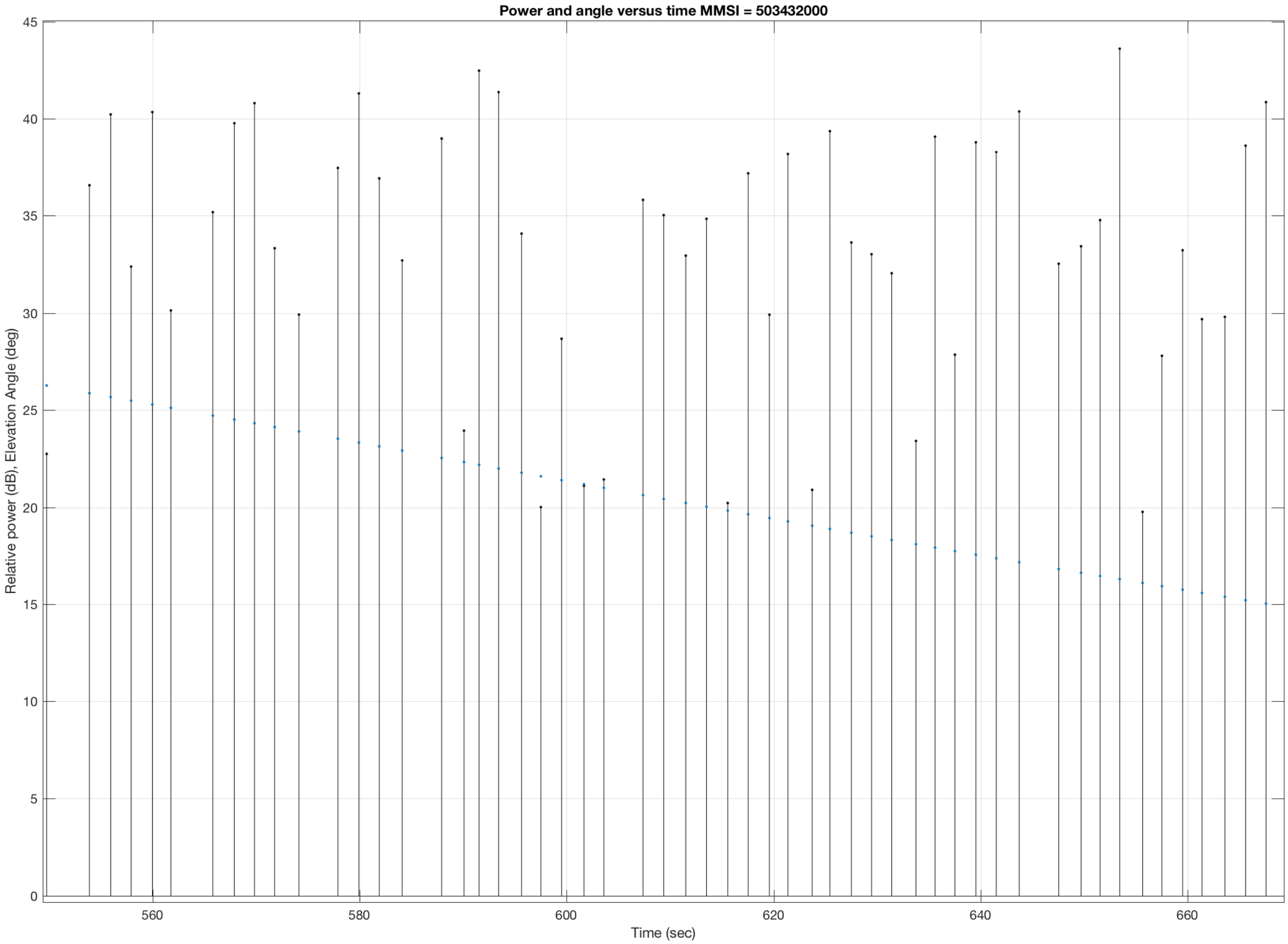


Note: as before, many more passes are at lower elevation angles making low angles appear denser

Satellite Channel Model
Channel Stability

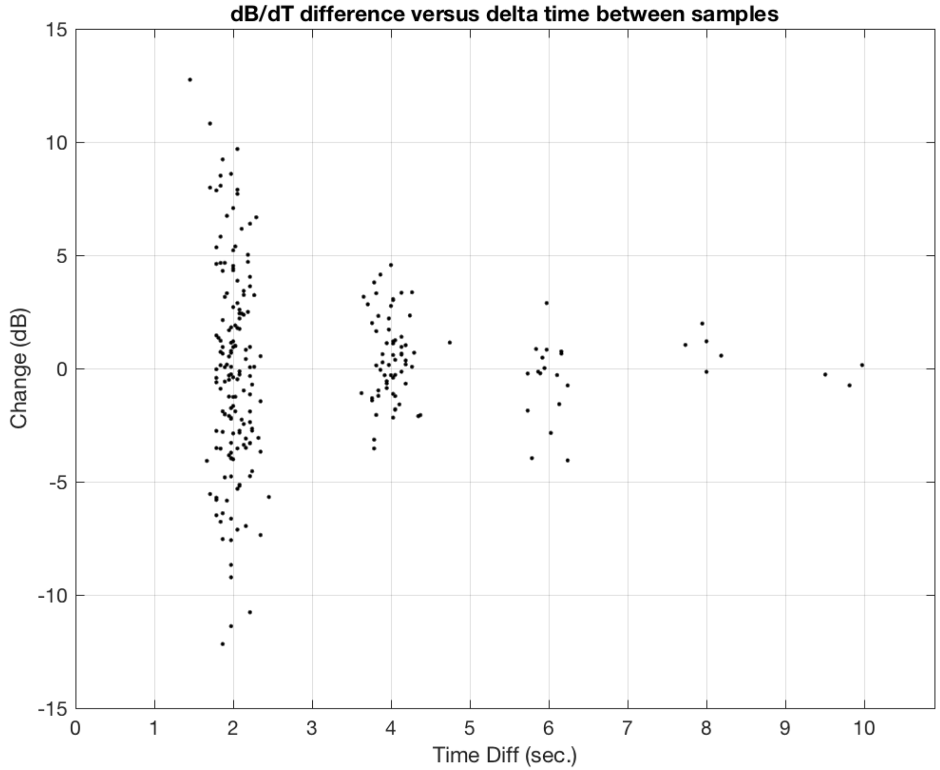
- Fading can be quite rapid
- Between messages a change of many dB in power level is common
- The amount of change does not appear to change with elevation angle or time
- On a dB per second basis the range is between fraction of a dB/s and up to 10 dB/s
- Challenge is the relatively long interval between messages for most ships (2 sec +) when AIS is used as a signal of opportunity
- Analysis ongoing - the rate of the fading is yet to be quantified

Satellite Channel Model – Channel Stability



Satellite Channel Model
Channel Stability (continued)

- Looking at the change in signal level from message to message (dB) and dividing by spacing of messages, a dB/dT figure can be derived (= dB/second)
- The values for dB/dT are plotted against the time difference between messages at right
- Quantifying this is important for the robustness of longer messages, such as the bulletin board
- Fading will also impact ability to manage traffic on the satellite VDES VDL



Results:

- 88% of samples changing less than 10 dB per second for 2 successive detections
- 81% less than 3 dB/s
- 62% for < 1 dB/s change, and
- only 27% of the points changed less than 0.3 dB/s (which could be considered negligible)

Satellite Channel Model
Doppler Shift

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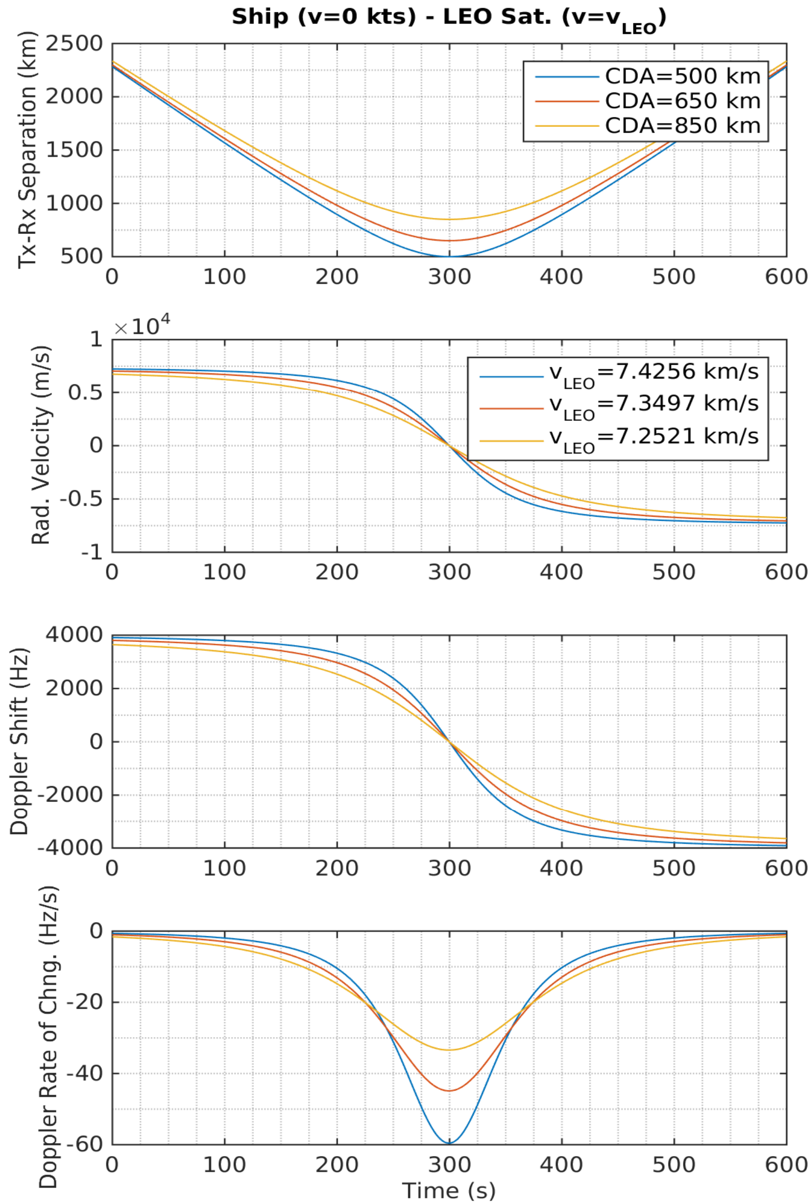
- One well-known characteristic of the satellite channel model to a low earth orbiting satellite is a high and rapidly changing frequency due to Doppler shift
- Vessels located along the sub-satellite line of travel experience the highest shift, while those at furthest cross-track locations experience relatively little
- The frequency change expected for VDES is approximately +/- 4 kHz, and the majority of this can occur over only 3 minutes for an overhead pass



Satellite Channel Model
Summary and Recommendations

- The exactEarth provided satellite AIS signal (relative) power versus elevation angle database has provided a very rich dataset from which to assess the VHF satellite channel large and small scale variations
- The large scale signal variations are due primarily to free space loss and AIS VHF antenna type and gain pattern, the expected path loss variation over the full range of elevation angles is only between 2 and 4 dB, compared to a free space loss variation predicted of 11 dB – this is very good news for link design (large scale channel model characteristic)
- An important implication is that the system can, and should be expected to operate well down to, and even below the point of the horizon (earth's limb)
- Contact time is very limited at higher elevation angles, so optimization of system for operation under such conditions is not recommended
- Small scale fading was found to be both very high, and rapid, having a Nakagami distribution with parameter value between about 0.6 and 1.5, with average of 0.85
- This is a harsher fading channel than what had been characterized for both GLA and the Tokyo Harbour trials

Satellite Channel Model
Summary and Recommendations

- The exactEarth data also demonstrated that the range of detectable signal power for a sensitive receiver can be quite high, if the system is able to make use of it
- Discouraging news was regarding the apparent rate of channel fast fading (Nakagami distribution)
- Estimates of this fading rate were performed, with 88% of samples changing less than 10 dB per second for 2 successive detection, but only 81% less than 3 dB/s, 62% for < 1 dB/s change, and only 27% of the messages had a change of less than 0.3 dB/s (which could be considered negligible)

Satellite Channel Model
Some caveats regarding the measurements

- Unfortunately the transmission rate, and sometimes detection rate of standard AIS limits the quality of the temporal record, however the analysis was developed to extract the maximum possible insights from the data available
- The fading was measured only using the AIS messages, which have an occupied bandwidth of 11 kHz, or so
- This means that frequency selective fading could not be assessed using single AIS position report messages
- It is expected that the small scale fading will be no better, and possible worse for longer and wider bandwidth message proposed for the VDES-SAT standard (especially 90 slot BBS broadcast)

Satellite Channel Model
Possible Follow-up Points

- Differential analysis of AIS channel 1 and 2 data to determine if evidence for and the amount of frequency selective fading can be estimated
- Calibrated measurements of signal level to a satellite for a pass to confirm large scale fading factors – closer to the median or peak signal level results?
- Use of long AIS messages received by satellite to look for evidence of fast fading

Document Reference

- VDES Channel, Noise and Interference Characteristics Document
- Available for download from Jeffrey's FTP server:
  - ftp://ftpcomms@ftp.e-navigation.nl/201702_intersessional/WORKING_INPUT/Channel_Model/20161104-VDES_Channel_Noise_and_Interference_Characteristics-0v3.docx
  - Password: Merma1d#
- Update expected prior to ITU WP5-B in April, 2017