Appendix A: Estimation of Losses due to atmospheric gases and cloud

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This document provides additional details of the approach that was used to analyze atmospheric gas and water vapor attenuation and Liquid Water Content (LWC) attenuation for the CA-HI Path 10 GHz project that was reported in DUBUS[i] Vol 52.

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Data Sources

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Determining the attenuation of an RF signal along its path within the duct requires both knowledge of the height of the upper and lower boundaries of the duct for each location along the RF signal's great circle path and also knowledge of the values of the parameters that affect the attenuation of the RF signal for each position within the duct namely temperature, pressure, humidity, and liquid water content. Estimates of these parameters can be obtained by using meteorologic data that is available from several sources. During the course of this project at various times and for various purposes three sources were used for this data: [1] National Weather Service Upper-air Observations Program[ii] radiosondes located at the California and Hawaii ends of the path, [2] the MAGIC[iii] study database, and [3] the Clouds and the Earth's Radiant Energy System (CERES) meteorologic satellite project[iv,v]. These sources are complementary, and because each of these sources is imperfect, incomplete, or both, in some cases it is necessary to combine data from these sources. Here is a brief discussion of each of these data sources.

Radiosonde data. The first potential source of temperature, pressure, and humidity / water vapor density data is NWS radiosonde data from San Diego, CA and Hilo, HI. These two locations approximately mark the two ends of the CA-HI RF path used in this project.

Radiosonde data has the important advantages of providing excellent vertical resolution and of being a well-established modality providing generally reliable data..

However NWS radiosonde data has several important disadvantages. First, and most importantly, the data is available only for the two ends of the CA-HI RF path and not for the points in between these two endpoints. This is a problem because, while base inversion height and duct height have been shown to smoothly progress along the path from CA to HI[vi] (although not in a linear fashion) and can be estimated along the path, a smooth and predictable progression for water vapor density as one moves east to west along the path has not been quantitated. Thus, while it is reasonable to interpolate duct dimensions and height along the path in order to estimate duct dimensions and height for locations along the path between the two endpoints, there is no justification for doing the same with water vapor density which is a necessary component of the calculations of atmospheric gas and water vapor attenuation. Thus a method other than the NWS-radiosonde data must be used to obtain estimated values of this parameter for points along the path.

A second issue is that the NWS radiosonde data is obtained at physical locations that are close to, but not the same as, the operating sites. Local geography may lead to important differences in atmospheric conditions for a given altitude between the radiosonde's location and the location of the operations.

A third issue is that liquid water content is not directly available from the NWS radiosonde data.

NWS radiosonde data was used during the project on a daily basis for estimating likely duct conditions for each day of operation. It was also used for testing various analytic strategies. However, because the data was limited to the two ends of the path, NWS radiosonde data was not useful for analyzing attenuation across the CA-HI path.

MAGIC data. The second potential source of data for estimates of temperature, pressure, humidity / water vapor density is the data from the MAGIC study which was conducted in 2012/2013 with radiosondes being launched every 6 hours from a ship traveling along a path between Los Angeles and Honolulu. The MAGIC study dataset includes but is not limited to surface meteorological data, rawinsonde (radiosonde with wind direction and velocity also supplied via radar tracking or radio direction finding techniques) data, ceilometer data, and microwave radiometer data[vii]. This data set has the disadvantage that the observations for the most part do not fall along the RF path between the two operating sites, although the sample locations do stay within 2 degrees of the RF path as can be seen in Figure 6 below where the ship's path is shown in red and the great circle RF path is shown in blue:

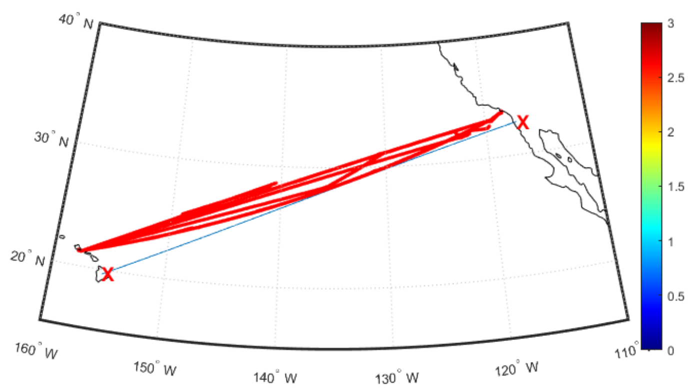

Figure 1. The path of the MAGIC study ship is shown in red and the RF path is shown in blue. A red "X" marks each end of the CA-HI RF path used in this project. This image is also available here.

The MAGIC study also has the disadvantage that, because data was collected at any point in time only for the single location along the path occupied by the ship at that moment, there are a limited number of observations in the data set. A third disadvantage is that a temperature inversion at the test location was not present during all observations, further reducing the number of useful data points available.

Importantly, liquid water content is not included in the MAGIC data set although a related parameter, liquid water path[viii], is available from the microwave radiometer data contained in the primary MAGIC data set[ixx]. Unfortunately, because liquid water path includes the entire (summed) liquid water content contained along the microwave radiometer's interrogating ray (mg/m^2), the liquid water path measurement cannot be used to determine what is required, namely the liquid water content (mg/m^3) of a volume element representing a small segment of the path spanned by the interrogating ray, given that the distribution of liquid water along the path is unknown.

There is an extensive literature on estimating LWC concentrations from radiosonde data extending back to the 1970s. Yuan[xi] has noted that one of the most commonly referenced / used methods, the Salonen-Uppala[xii] method, significantly underestimates LWC in tropical environments. Yuan proposed an alternative method that uses water vapor pressure to set the humidity threshold that he subsequently validated in several tropical locations. Other methods for obtaining LWC from radiosonde data have been described by Decker[xiii] and Mattioli[xiv], who proposed both a modification of the Salonen-Uppala method and an original new method. When we evaluated the accuracy of the results of these 5 methods by comparing their results to CloudSat LWC measurements obtained from the same data set, we found that all five of these techniques for calculating LWC from radiosonde data substantially underestimated LWC as compared to the CloudSat measurements for our CA-HI path. So while the gaspl estimates from MAGIC are considered to be reliable, LWC estimates based on these methods are not.

CERES Project satellite data. The third potential source of data for estimates of temperature, pressure, water vapor density, and liquid water content is satellite data derived from the CERES project. The CERES project combines and time-correlates the data from multiple weather satellites traveling in formation along an inclined orbit that over the course of a month gives multiple passes over the points along the RF path between CA and HI. The figure below shows the ground tracks for the points in the CERES data set used in this project superimposed on the great circle path between San Diego and Hilo:

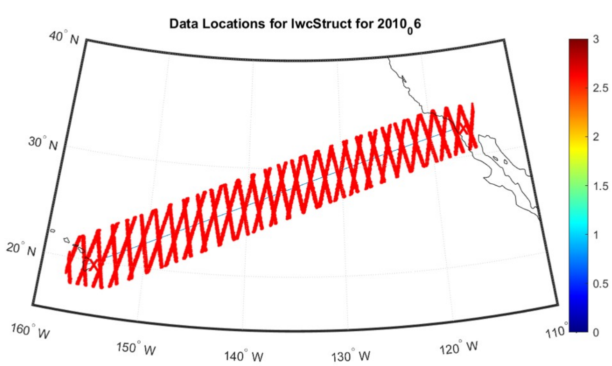

Figure 2. CERES ground track for data points used in this project. This is also available here.

Each Ceres data point provides a complete set of measurements for heights extending from ground or sea level to well above the height of the temperature inversion and its resultant duct that occupy the interest. Using the data from the CERES project, it was possible to obtain and analyze simultaneously obtained temperature, pressure, water vapor pressure, and liquid water content data from multiple points along and located within 2 degrees of the RF (great circle) path between the operating sites for the summer months of 2007-2010 inclusive, obtaining more than 3 million individual data sets along the RF path during that time period. Data analysis was limited to this 4-year period because, due to (US Federal government) funding considerations, subsequent CERES project data, although collected, has not been processed or made available by the CERES project team (as of the time of the writing of this report).

Method for estimation of attenuation by atmospheric gases

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ITU Recommendation ITU-R P.676-13 (08/2022) titled "Attenuation by atmospheric gases and related effects" details the method used in this project for determining propagation losses due to atmospheric gases for locations within the duct[xv]. This is a complex method that requires multiple table lookups. Fortunately, MATLAB provides an implementation of this method in their **gaspl** function[xvi] that performs these complexities, and in this project this function was used except for frequencies below 1 GHz. For frequencies below 1 GHz, estimates of attenuation were obtained by using the MPM93[xvii,xviii] software, an update of the MPM87 software described by Liebe and Layton in 1987[xix].

Performing these attenuation calculations requires knowledge of several parameters:
Path Length
Frequency
Temperature
Atmospheric Pressure
Water Vapor density

Path length and frequency are known quantities, and estimates for temperature, atmospheric pressure, and water vapor density at multiple altitudes including altitudes within the duct are available from each of the three data sources enumerated and discussed above.

Method for estimation of attenuation by liquid water content

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The method used for calculating liquid water attenuation is based on ITU Recommendation ITU-R P.840-8, "Attenuation due to clouds and fog", equations 1-11[xx]. This is implemented in MATLAB as the routine fogpl[xxi]. For this project I used both fogpl and a MATLAB routine based on the ITU recommendation that I wrote prior to becoming aware of the MATLAB fogpl routine. My implementation and fogpl give equivalent results. No table lookups are required for the MATLAB methods.

Performing these calculations requires knowledge of these parameters:

Path Length
Frequency
Temperature
Liquid water content

Path length and frequency are known quantities, and estimates for temperature and liquid water content (LWC) are available from the Ceres satellite data set. In addition, LWC can also be estimated from the MAGIC radiosonde data using several methods as mentioned above. However, these methods proved to be inaccurate in our testing as described above and so are not included in the final results section.

Determination of duct height and dimensions

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For the satellite data set models (Model 1 and Model 2) duct height was determined by deriving the base inversion height from the satellite data set temperature/height curve for each data point. Upper and lower duct thickness were respectively added to or subtracted from the base inversion height to obtain top duct height and bottom duct height for each data point. The duct thicknesses were derived from a 3rd order polynomial regression of top or bottom duct thickness respectively vs distance obtained from the MAGIC data set.

For the MAGIC data set model (Model 3) duct top and bottom heights were obtained directly from the MAGIC radiosonde dataset.

Special considerations when calculating gaspl and LWC attenuation for the entire path

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In order to calculate gaspl attenuation and LWC attenuation for the entire path between the San Diego and Hawaii locations, one must first calculate the average attenuation coefficient for each of these two types of attenuation for each available data point along the path, accepting data points that are within 2 degrees of the path.

The number of data points available along the path that contain a duct is not uniform as a function of distance along the path. For the data set as a whole, there is a decrease in the number of such available data points per 500 km distance interval in the middle of the path as compared to the two ends of the path, as is shown in the histogram immediately below. Furthermore, as one moves along the path from San Diego towards Hawaii there is a substantial and significant decrease in the number of available data points per 500 km segment when the data set is limited to those locations with 100% cloud cover as is shown in Figure 22 below. The 100% cloud cover data set contained 978,467 data points or 28% of the full data set.

The rationale for including subset analysis for those locations showing 100% cloud cover in this project was [1] as noted in the main body of this report some authorities have suggested that complete cloud cover along the path is a necessary accompaniment of optimal ducting along the path, and [2] the presence of 100% cloud cover would be expected on the basis of the theory given above to substantially increase the total path attenuation produced by liquid water content. So estimating the path attenuation that would be expected under 100% cloud cover is an important part of this project, and we modeled those conditions by filtering the entire data set to create a data set that includes only those data points for which there is 100% cloud cover. When we refer to “100% cloud cover” in this and related documents, we are referring to results obtained with this model.

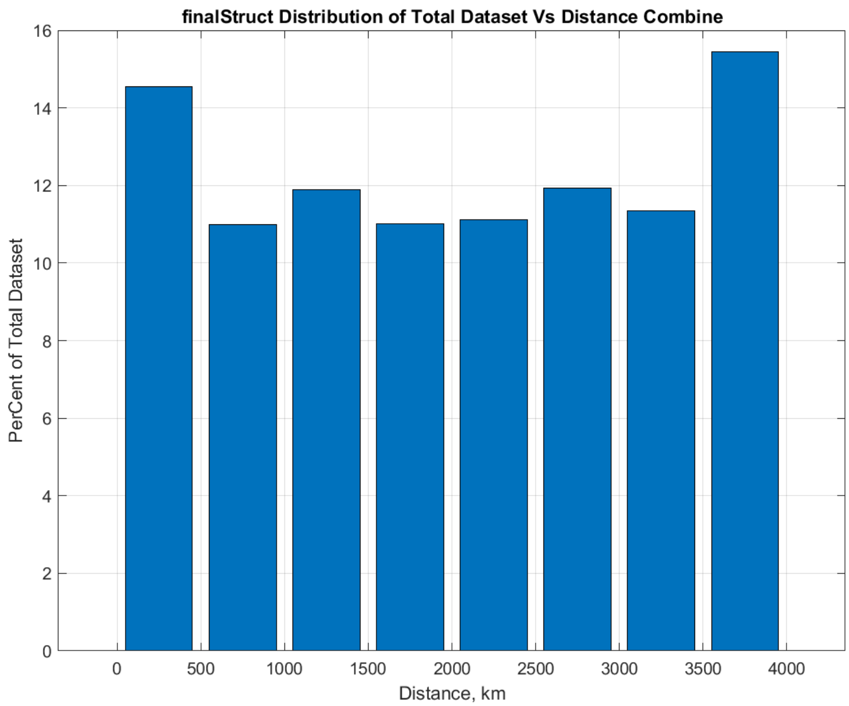

Figure 3. Distribution of data points within 500 km intervals along the path from San Diego to Hawaii for the entire data set. This figure is also available here.

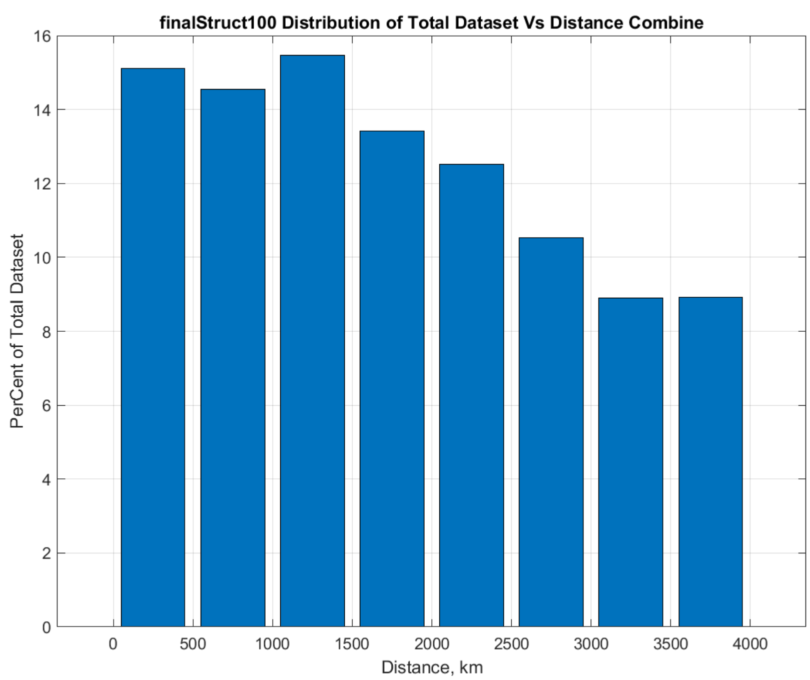

Figure 4. Distribution of data points within 500 km intervals along the path from San Diego to Hawaii for locations with 100% cloud cover. This figure is also available here.

To prevent a skewing of the results because of the non-uniform data point density in the distance dimension described above, the results for data points in each 500 km distance interval were calculated separately, in order to ensure that each 500 km segment of the path contributed equivalently to the overall result.

Total path attenuation for each attenuation modality was determined for each point by calculating the attenuation coefficient for each voxel at that location, then applying the appropriate partial volume correction to the result for those voxels in order to obtain the average attenuation coefficient present across the face of the duct at that location. This was done for each geographic location in the data set. The mean of the attenuation coefficient values obtained in this manner in a given 500 km distance segment along the path was then calculated and this average value was used to represent the attenuation across that 500 km segment. The attenuation values thus obtained for each 500 km segment were averaged and this mean value was multiplied by the path length of 4086 km to give the total attenuation across the entire path.

Models used for estimating attenuation across the path

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Results are presented below for two slightly different satellite-based methods for estimating loss across the path. The first method (Model 1 in the table below) used base inversion height obtained directly from each individual satellite-based measurement to set the height of the duct for that measurement.

The second method (Model 2 in the table below) instead used the entire ~3.5 million point satellite data set that was used for this project to derive a 3rd order polynomial to set the base inversion height.

The MAGIC study data could reliably provide an estimate only for gaspl attenuation, which was 54 dB.

Results

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A summary of the results of these three methods is shown in the table below. Values shown are the mean for the entire data set. Path loss in dB is for a path length of 4086 km. The last four columns show results under 100% cloud cover conditions; the first four columns are for the complete data set. “Total Att” is combined gaspl and LWC attenuation.

	(dB)	(mg/m^3)	(dB)	(dB)	100% CC	100% CC	100% CC	100% CC
Method	Gaspl	LWC	LWC Att	Total Att	Gaspl	LWC	LWC Att	Total Att
Model 1	60	192	57	116	57	269	80	137
Model 2	57	180	52	109	59	277	80	139
MAGIC	54	NA	NA	NA	NA	NA	NA	NA

Table 8. Summary of results obtained using models 1-3. Mean values for entire data set are shown.

Results among these 2 models were reasonably consistent. For the entire data set, atmospheric gas and water vapor (gaspl) attenuation was 60 dB across the path for model 1 and 57 dB for the other satellite-based model 2. The MAGIC estimate of gaspl attenuation was slightly lower, 54 dB. LWC values within the duct ranged from 180-192 mg/m^3 and LWC attenuation within the duct ranged from 52-57 dB. Gaspl plus LWC attenuation within the duct for the entire data sat was 109-116 dB.

Under 100% cloud cover gaspl attenuation was similar to the results for the entire data set, 57-59 dB. However, LWC with 100% cloud cover was substantially higher, at 269-277 mg/m^3 and LWC attenuation was also substantially higher at 80 dB. Gaspl plus LWC attenuation under 100% cloud cover was 137-139 dB, also substantially higher than under average conditions.

There is significant temporal variability in conditions across the CA-HI path, which especially affects the LWC and LWC attenuation. The table below shows the minimum/maximum values of the monthly average for each parameter shown in table 8 for models 1 and 2. These cover the entire study period from June 2007 through July 2010.

	(dB)	(mg/m^3)	(dB)	(dB)	100% CC	100% CC	100% CC	100% CC
Method	Gaspl	LWC	LWC Att	Total Att	Gaspl	LWC	LWC Att	Total Att
Model 1	57/62	149/243	43/71	104/132	55/60	194/349	57/101	116/160
Model 2	54/59	128/217	37/65	96/120	55/62	177/344	51/99	113/160

Table 9. Summary of results obtained using models 1 and 2. Minimum and maximum monthly averages for entire data set are shown.

Summary

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Under “average” conditions, on average the combined gaspl and LWC attenuation across the CA-HI duct on 10 GHz is expected to be on the order of 109-116 dB.

Using our model of 100% cloud cover, on average the combined gaspl and LWC attenuation is on the order of 137-139 dB.

The information in this appendix may change as we further analyze the data. Check back for updates. If the date following my signature and call sign below is more recent than the date given on the version of this document that you have been reading, then there will be portions of this document that are different than the one that you have previously read.

I am currently writing an expanded document covering the basic physics of duct formation which also contains a much more extensive consideration of the details of the analysis of duct attenuation than could be covered in this document. This should be available here by May 2023

References are found on the next page.

--Roger Rehr W3SZ 3-14-2023

Bibliography

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i Moncur R, Rehr R, Lauterbach G, Bailey G: “Results and Analysis of Attempt at Extending the 10 GHz Terrestrial World Record on the Hawaii-California Path”, DUBUS, 2023, 52(1):28-50.

ii https://www.weather.gov/upperair/

iii Alappattu DP, Wang Q, Kalogiros J: “Anomalous propagation conditions over eastern Pacific Ocean derived from MAGIC data”, Radio Sci., 51, 1142–1156, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016RS005994

iv Ceres Project, https://ceres.larc.nasa.gov/

v Kato S, Ham S, Miller WF et al.: “Variable Descriptions of the A-Train Integrated CALIPSO, CloudSat, CERES, and MODIS Merged Product (CCCM or C3M)”, 2021, https://ceres.larc.nasa.gov/documents/collect_guide/pdf/c3m_variables.RelD1.20211117.pdf

vi Purves CG: “Geophysical aspects of atmospheric refraction”, NRL Report 7725, Washington, DC, 1974, 23-28.

vii https://armweb0-dev.ornl.gov/data/data-sources

viii https://climatedataguide.ucar.edu/climate-data/liquid-water-path-overview

ix https://adc.arm.gov/discovery/#/results/site_code::mag/primary_meas_type_code::liqwaterpath

x Painemal D, Greenwald T, Cadeddu M, Minnis P: “First extended validation of satellite microwave liquid water path with ship-based observations of marine low clouds”, , Geophys. Res. Lett., 2016, 43, 6563–6570. https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL069061

xi F. Yuan, Y. H. Lee, Y. S. Meng and J. T. Ong: "Water Vapor Pressure Model for Cloud Vertical Structure Detection in Tropical Region," IEEE Transactions on Geoscience and Remote Sensing, 54:5875-5883, Oct. 2016, doi: 10.1109/TGRS.2016.2574744.

xii Salonen E, Uppala S: “New prediction method of cloud attenuation”, Electronics Letters, 1991, 27:1106-1108.

xiii Decker M, Westwater E, Guiraud: “Experimental Evaluation of Ground-Based Microwave Radiometric Sensing of Atmospheric Temperature and Water Vapor Profiles”, Journal of Applied Meteorology,1978, 17:1788-1795.

xiv Mattioli V, Basili P, et al: “Analysis and improvements of cloud models for popagation studies”, Radio Science 44:1-13, 2015, doi:10.1029/2008RS003876.

xv ITU Recommendation ITU-R P.676-13 “Attenuation by atmospheric gases and related effects”, https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.676-13-202208-I!!PDF-E.pdf

xvi https://www.mathworks.com/help/phased/ref/gaspl.html

xvii https://its.ntia.gov/research-topics/radio-propagation-software/mpm/millimeter-wave-propagation-model-mpm/

xviii MPM93 software may be downloaded from the NTIA website via this link: https://its.ntia.gov/media/35413/mpm93.zip

xix Liebe HJ, Layton DH: “Millimeter wave properties of the atmosphere”, NTIA Tech Report TR-87-224,1987. Available for download from NTIA website via this link: https://its.ntia.gov/umbraco/surface/download/publication?reportNumber=87-224.pdf

xx ITU Recommendation ITU-R P.840-8 “Attenuation due to clouds and fog”, https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.840-8-201908-I!!PDF-E.pdf

xxi https://www.mathworks.com/help/phased/ref/fogpl.html