Frequency Estimator Performance for a Software-Based Beacon Receiver

Session 434: Propagation and Scattering in Random or Complex Media

Michael J. Zemba, Jacquelynne R. Morse, and James A. Nessel
NASA Glenn Research Center
Cleveland, OH

Keeping the universe connected.

www.nasa.gov

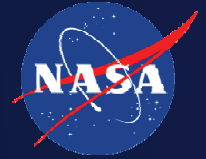*July 10th, 2014* • *2014 IEEE AP-S & USNC-URSI* • *Memphis, TN*

Presentation Overview

1. Technical Motivation
2. Site of Study
3. Beacon Receiver Hardware
4. Beacon Receiver Software
5. Frequency Estimators
6. Measured Results
   - Frequency
   - Doppler Shift
7. Conclusions & Future Work

Technical Motivation

Propagation studies at a given site are valuable in designing efficient, cost effective ground stations without sacrificing performance or availability. [1]

Original Signal Power

Troposphere
(7km – 20km)

Clouds

Atmospheric Gases
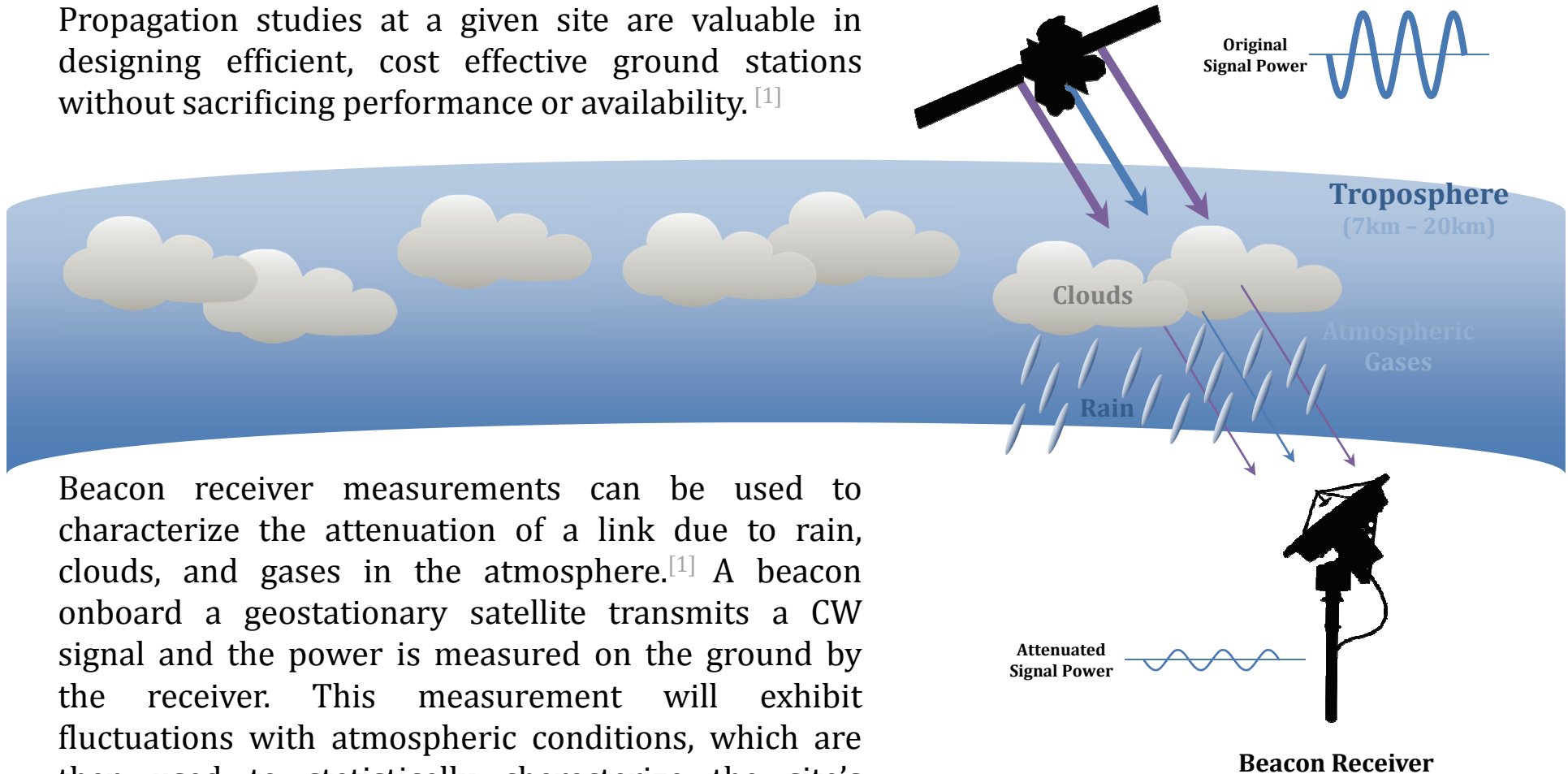
Rain

Beacon receiver measurements can be used to characterize the attenuation of a link due to rain, clouds, and gases in the atmosphere.[1] A beacon onboard a geostationary satellite transmits a CW signal and the power is measured on the ground by the receiver. This measurement will exhibit fluctuations with atmospheric conditions, which are then used to statistically characterize the site's atmospheric attenuation.

Attenuated Signal Power

Beacon Receiver

Site of Study

Milan, Italy
Rainfall: 67mm per month
Avg. Humidity: 73%
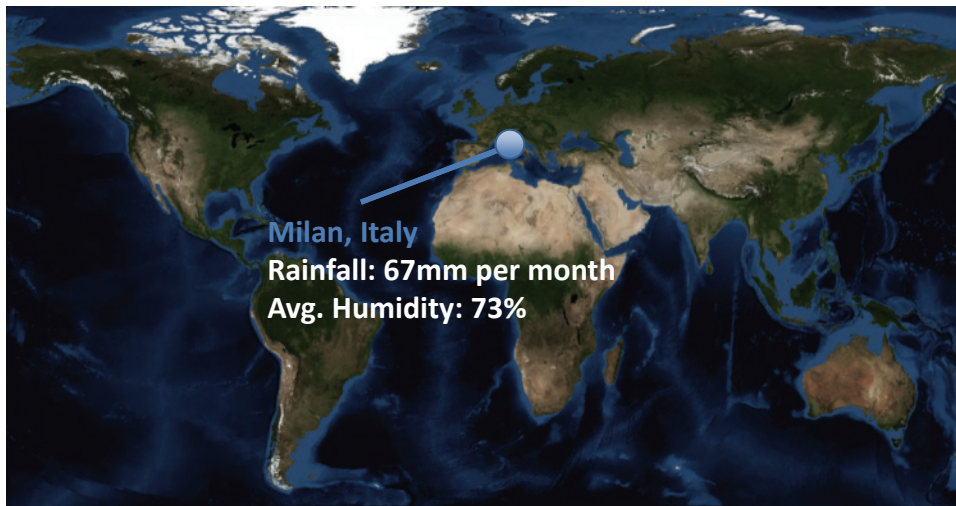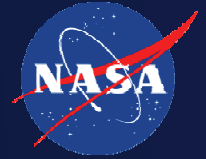
|		Milan, Italy
Ground Station	Installation Date	April 2014
	Latitude	45.4787° N
	Longitude	9.2327° E
	Altitude	121 m
Satellite	Name	Alphasat
	Elevation	48.6°
	Azimuth	170.2°
	Beacon Freqs.	19.701 GHz 39.402 GHz

To characterize atmospheric propagation effects at Ka-band (20 GHz) and Q-band (40 GHz), a dual Ka/Q-band beacon receiver was deployed to Milan, Italy in a collaboration between NASA Glenn Research Center and the Politecnico di Milano, utilizing the beacons onboard the Alphasat satellite (launched July 2013).
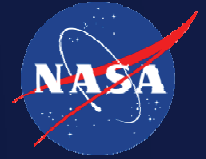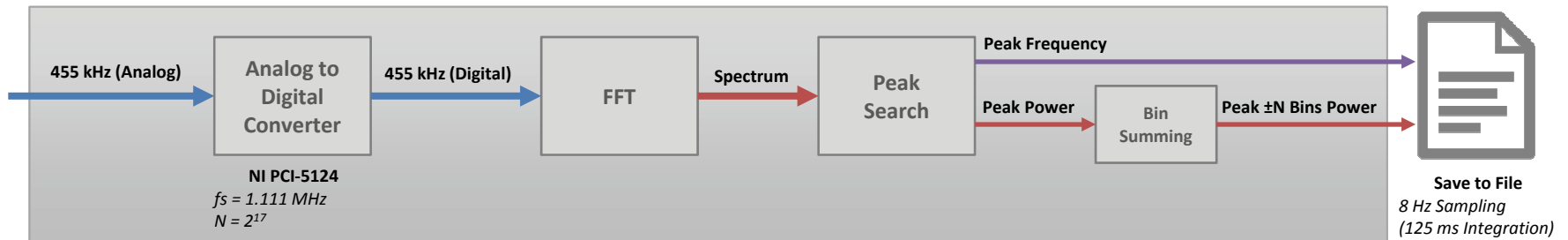
Beacon Receiver Hardware

System Specifications	
Downconversion (Ka)	3-step down to 455 kHz
Downconversion (Q)	4-step down to 455 kHz
Sampling Rate	1.111 MHz
Number of Points	2^{17}
Integration Time	125 ms
Time Series Output Rate	8 Hz
Dynamic Range	40 dB
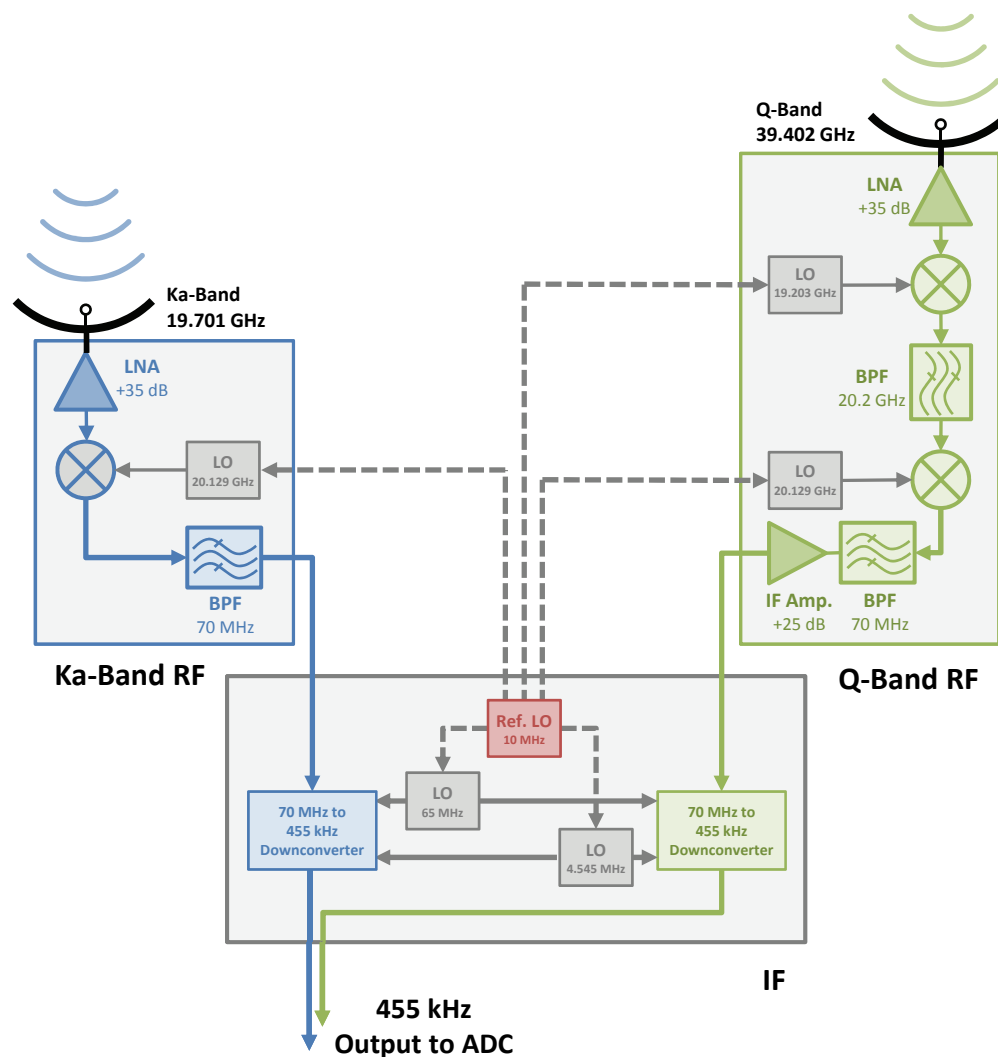
Beacon Receiver Software

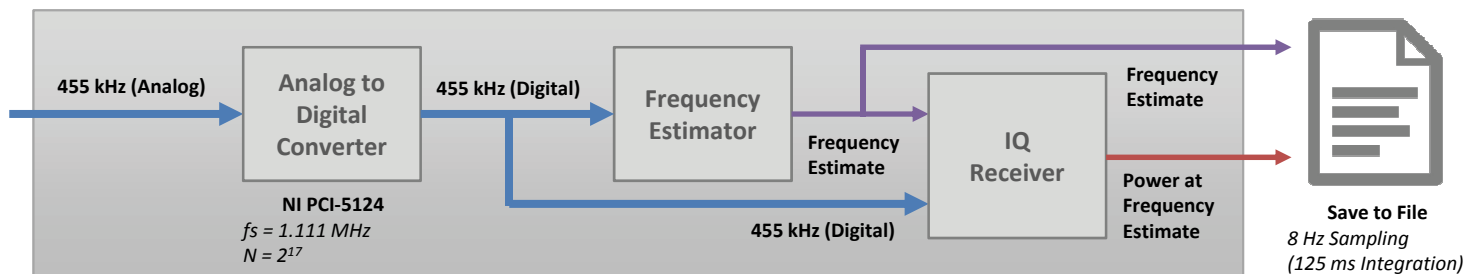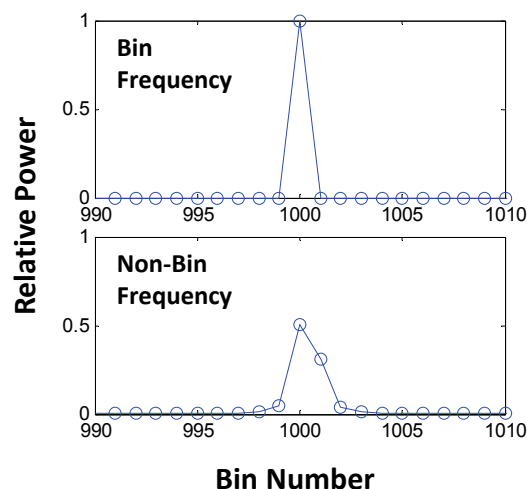**Basic FFT Approach**
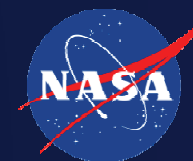

- Frequency Resolution of fs/N
- Error in Power Measurement (Scalloping)

Frequency Estimator Approach

- Increased Frequency Resolution & Accuracy
- Increased Power Measurement Accuracy (No Scalloping)
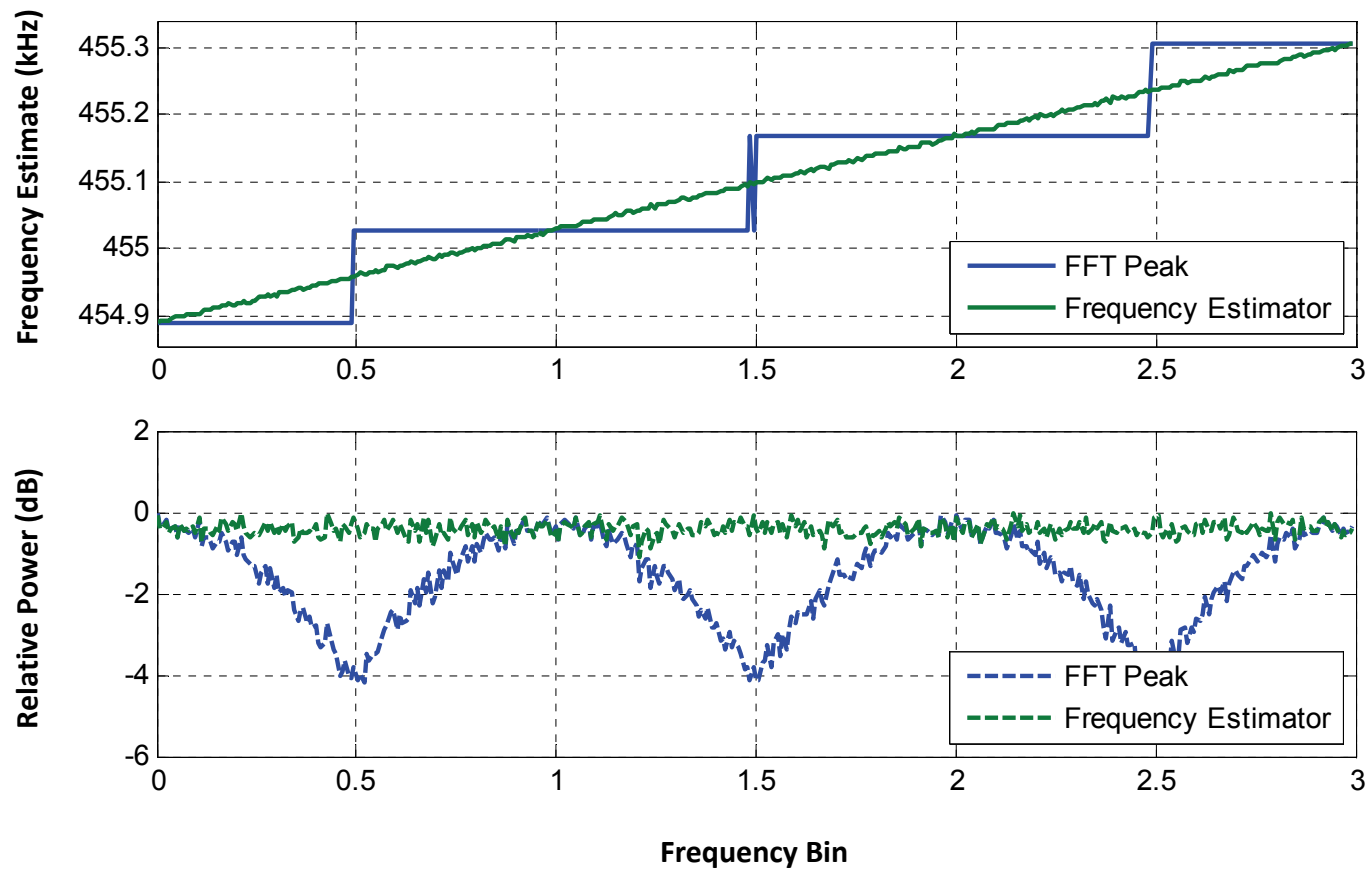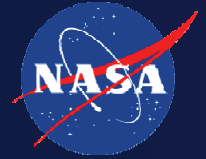
FFT Frequency Estimation

Although FFTs can be used to easily estimate frequency, the resolution is defined by bins of width $\frac{f_s}{N}$ (where f_s is the sampling frequency of the signal and N is the number of points). This requires careful selection of fs and N to set the desired resolution.

Additionally, when the frequency of the signal is not exactly a bin frequency, the power of the signal is distributed into neighboring bins. As the frequency of a signal drifts, this creates a scalloping effect in the power measurement.
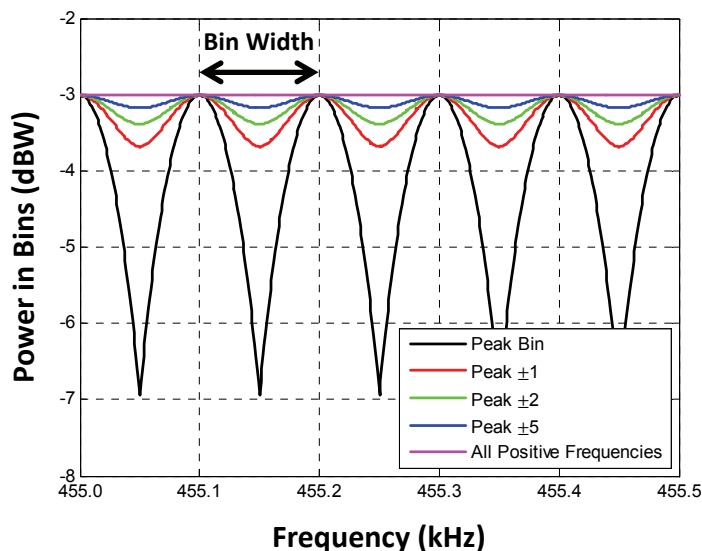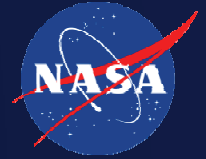
Alternatively, a variety of algorithms can be used to interpolate the frequency when it is between the bins of the FFT, giving us more freedom to select f_s and N based on other criteria, and stabilizing the power measurement.
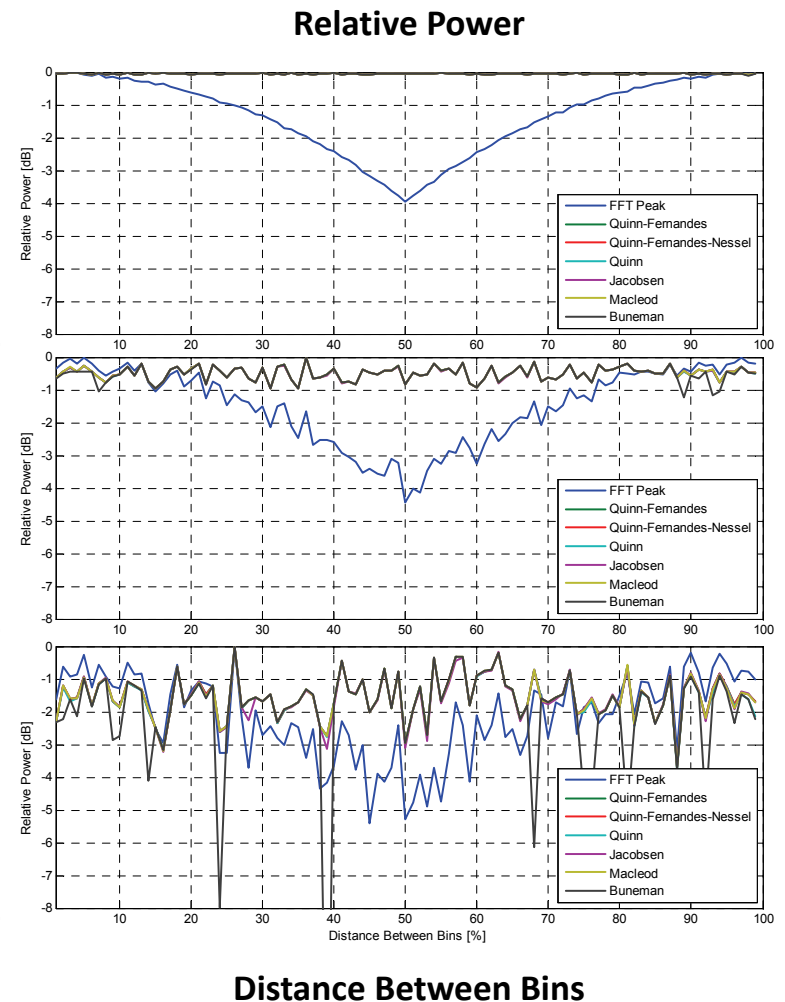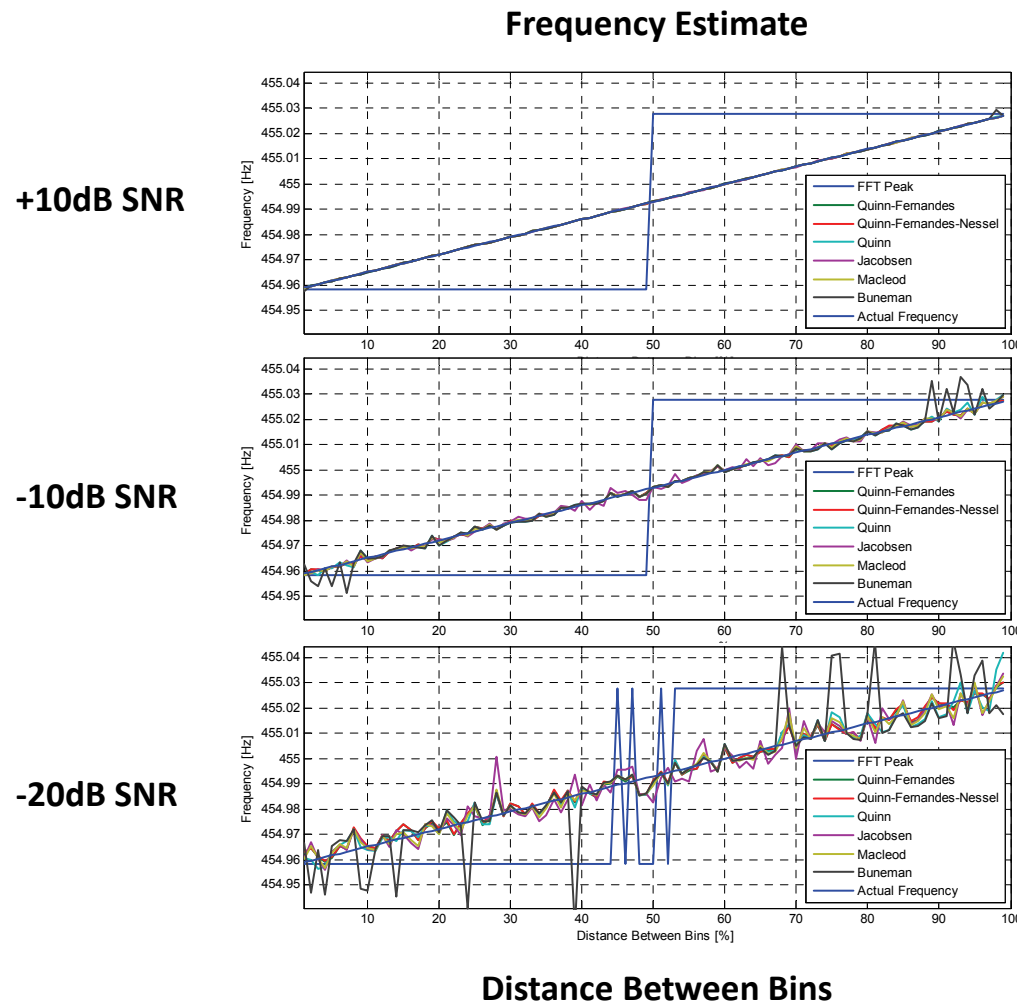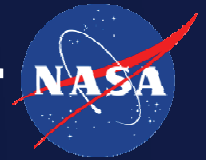
FFT vs. Frequency Estimator
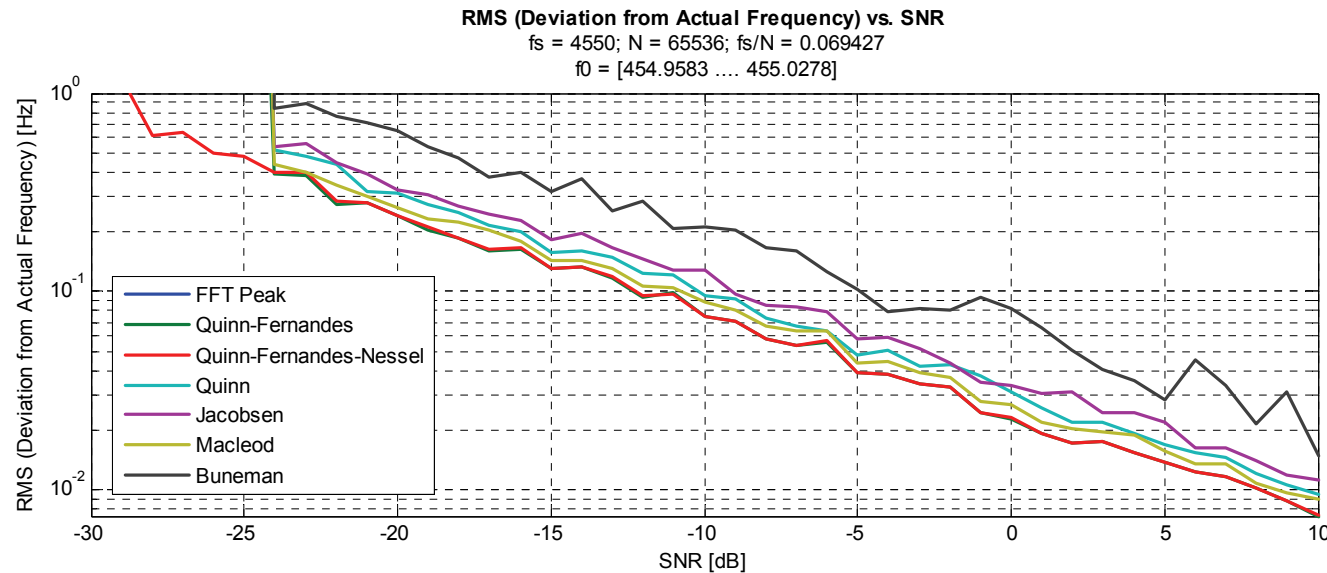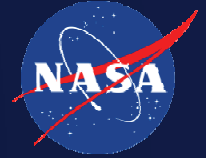
Frequency Estimation Algorithms

In addition to the FFT, the performance of six frequency estimators was simulated to select one for usage in the Alphasat receiver software:

- **FFT Peak** – Simply estimates the frequency by locating the peak bin of the Fast Fourier Transform.
- **Quinn-Fernandes** – *Quinn, B.G. and Fernandes, J.M., "A fast technique for the estimation of frequency", Biometrika, 78(3) (1991), pp. 489–497.*[2]
- **Quinn-Fernandes-Nessel** – The same implementation as the Quinn-Fernandes method above, but modified to include optional optimization through *a priori* frequency information.
- **Buneman** – A frequency estimation algorithm included in LabVIEW, *http://digital.ni.com/public.nsf/allkb/4D01B90 DCBAD81C0862570FC005A914E.*[3]

- **Quinn's Method** – *Quinn, B.G., "Estimating frequency by interpolation using Fourier coefficients," IEEE Trans. Sig. Proc. Vol 42 No 5, May 1994, pp1264-1268.*[4]
- **Jacobsen** – *Jacobsen, E.A., "On Local Interpolation of DFT Outputs," <http://www.ericjacobsen.org/FTinterp.pdf>, Fall, 1994.*[5]
- **Macleod** – *Macleod, M.D., "Fast Nearly ML Estimation of the Parameters of Real or Complex Single Tones or Resolved Multiple Tones," IEEE Trans. Sig. Proc. Vol 46 No 1, January 1998, pp141-148.*[6]

Simulated Frequency Estimate & Power

Frequency Estimate

Relative Power

+10dB SNR

-10dB SNR

-20dB SNR

Distance Between Bins

Distance Between Bins

RMS (Deviation from Actual Frequency) vs. SNR
fs = 4550; N = 65536; fs/N = 0.069427
f0 = [454.9583 .... 455.0278]

With SNR varying from -30 to +10 dB, each algorithm's error with respect to the actual frequency (RMS) is plotted on a semi-log scale above.

All six methods (excluding the FFT) exhibited an exponential increase in RMS error as the SNR decreases. At approximately -24 dB SNR, the noise at any point in the spectrum may exceed the peak of the FFT, and most of the methods therefore become unable to track the frequency. Quinn-Fernandes-Nessel manages to survive below this point because of the *a priori* information it is given on where to look for the peak.

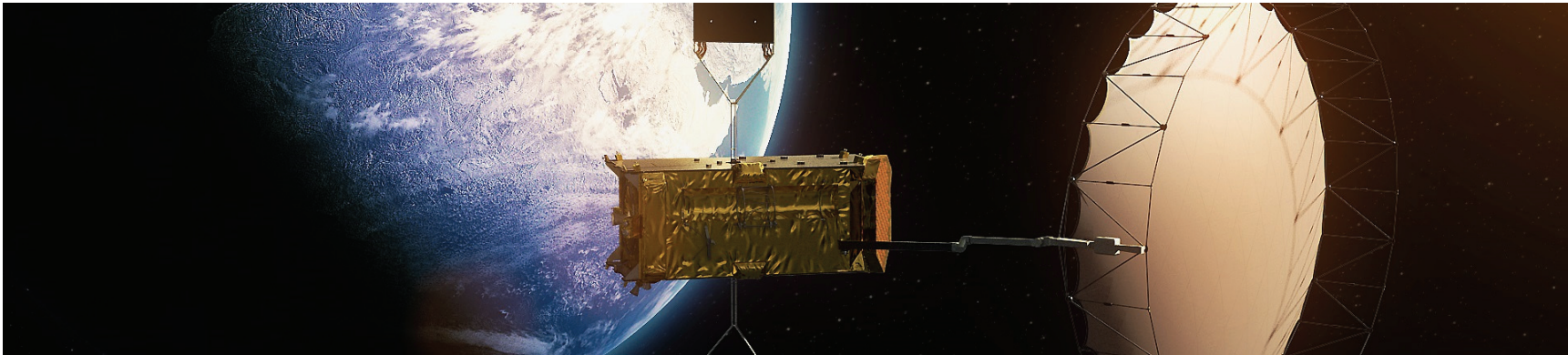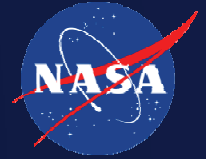# Measured Frequency

Measured Doppler Shift

Alphasat Deviation from Beacon Frequency
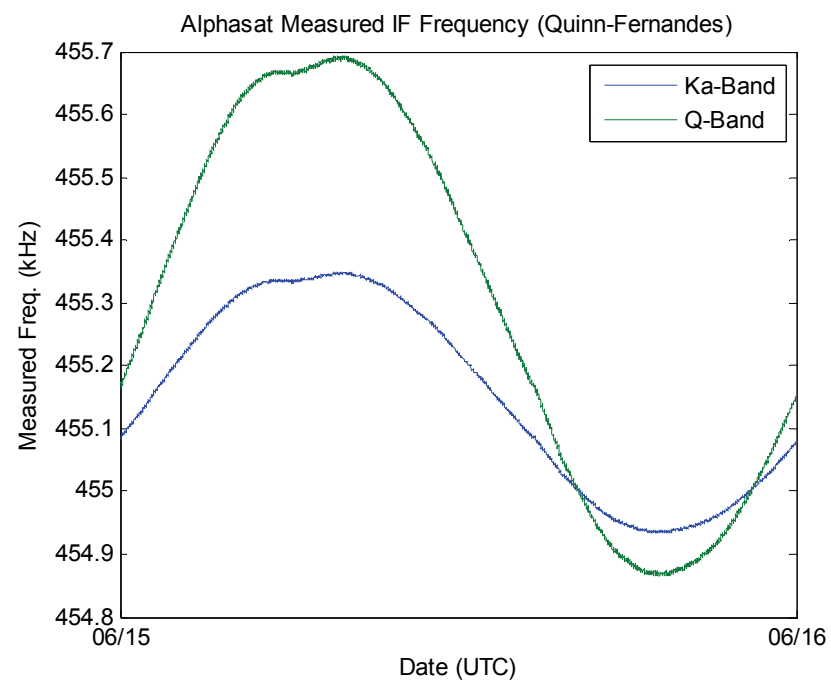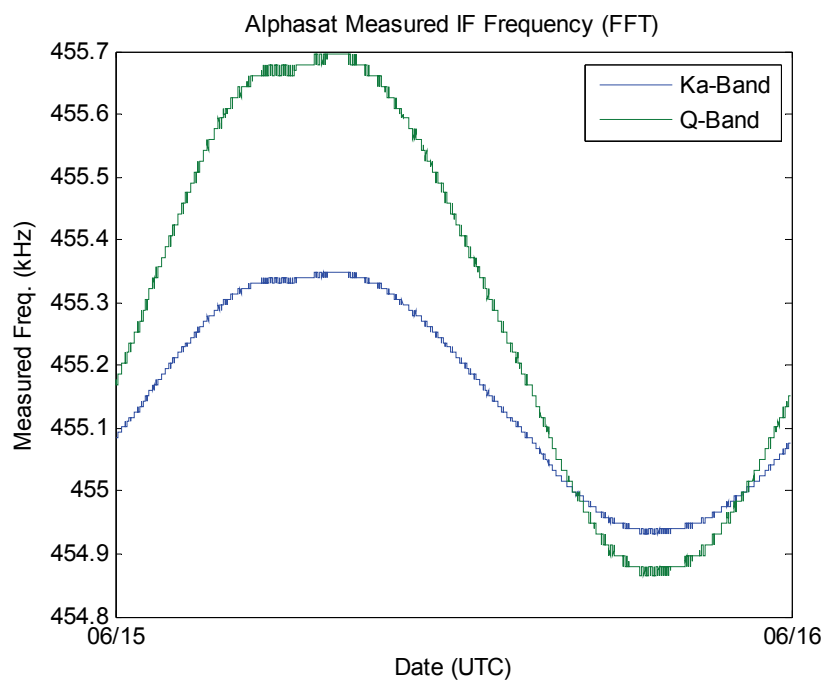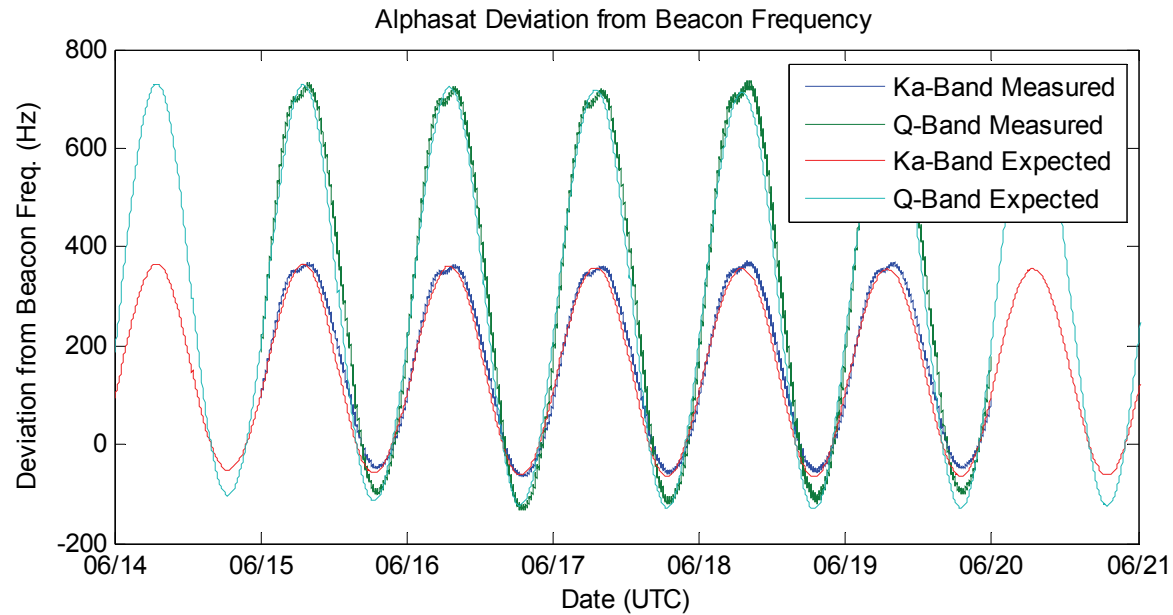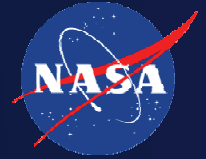
When compared to the expected doppler shift (derived from satellite position data), the beacon offset and drift can be estimated.

|	Drift	Offset
Ka-Band Beacon	15.7 Hz/day	150 Hz
Q-Band Beacon	31.6 Hz/day	300 Hz

Conclusions

Conclusions:

Both in simulation and in measurement, the estimator-based receiver proved more accurate than the purely FFT-based approach for both frequency and power measurements.

Most of the selected algorithms performed comparably; each estimator was shown to calculate the frequency to within ±1 Hz given an SNR above -24 dB, although the Buneman algorithm was eliminated for this application given its reduced performance near bin frequencies.

If operation at lower SNR is required, the inclusion of *a priori* information on where to search for the peak can be implemented to improve performance. This was implemented in the Alphasat receiver design, but only utilized during low-SNR conditions.
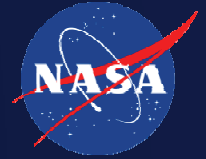
Future Work
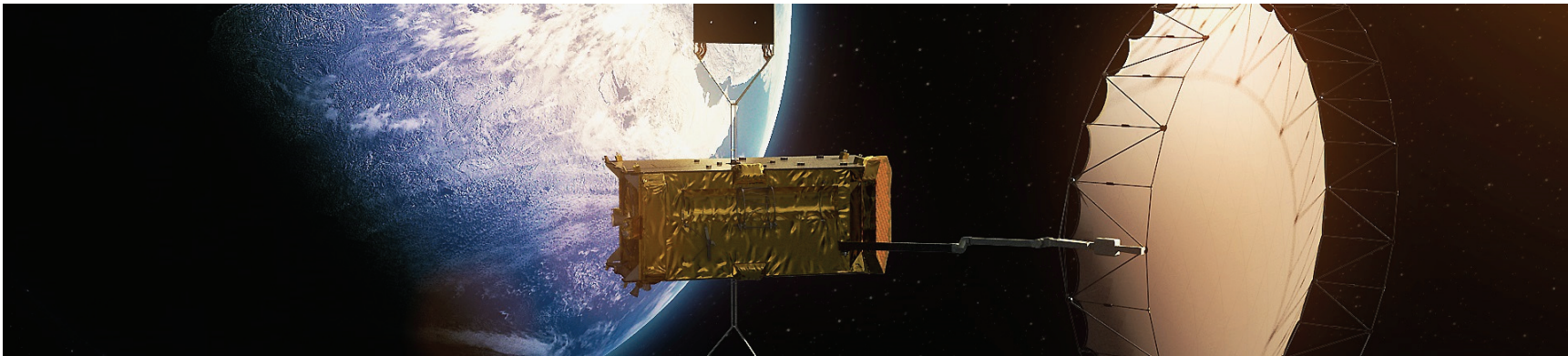
Future Work:

Near-Term:

- Continued Data Collection
  - ≥ *5 years*
- Statistical Characterization of Milan at 20 GHz & 40 GHz

Long-Term:

- Further Optimization of Receiver Algorithm for Future Iterations
- Additional Frequency Bands (V/W/Optical)
- Additional Sites

Contact Information

NASA Glenn Research Center
21000 Brookpark Rd. MS 54-1
Cleveland, Ohio 44135, USA

James Nessel
Principal Investigator, RF Propagation Task
216.433.2546
james.a.nessel@nasa.gov

Michael Zemba
Research Engineer
216.433.5357
michael.j.zemba@nasa.gov

Jacquelynne Morse
Research Engineer
216.433.5468
jacquelynne.r.morse@nasa.gov

Félix Miranda
Chief, Advanced High Frequency Branch
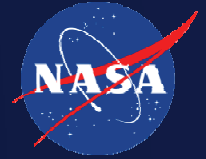216.433.6589
felix.a.miranda@nasa.gov

References

[1] A.R. Thompson, J.M. Moran, and G.W. Swenson, *Interferometry and Synthesis in Radio Astronomy*, Second Edition, John Wiley & Sons, 2001.

[2] Quinn, B.G. and Fernandes, J.M., "A fast technique for the estimation of frequency", Biometrika, 78(3) (1991), pp. 489–497.

[3] National Instruments. Buneman Frequency Estimator VI [Online] Available: http://digital.ni.com/public.nsf/allkb/4D01B90DCBAD81C0862570FC005A914E.

[4] Quinn, B.G., "Estimating frequency by interpolation using Fourier coefficients," IEEE Trans. Sig. Proc. Vol 42 No 5, May 1994, pp1264-1268.

[5] Jacobsen, E.A. "On Local Interpolation of DFT Outputs," Available: http://www.ericjacobsen.org/FTinterp.pdf, Fall, 1994.

[6] Macleod, M.D., "Fast Nearly ML Estimation of the Parameters of Real or Complex Single Tones or Resolved Multiple Tones," IEEE Trans. Sig. Proc. Vol 46 No 1, January 1998, pp141-148.

[7] R. J. Acosta, B. D. Frantz, J. A. Nessel, and D. D. Morabito, "Goldstone Site Test Interferometer," in 13th Ka and Broadband Communications Conference, Turin, Italy, 2007.

[8] R. J. Acosta, J. A. Nessel, and D. D. Morabito, "Data Processing for Atmospheric Phase Interferometers," in 14th Ka and Broadband Communications Conference, Matera, Italy, 2008.