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

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Presentation Overview

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

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.
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

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downconversion (Ka)</td>
<td>3-step down to 455 kHz</td>
</tr>
<tr>
<td>Downconversion (Q)</td>
<td>4-step down to 455 kHz</td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>1.111 MHz</td>
</tr>
<tr>
<td>Number of Points</td>
<td>$2^{17}$</td>
</tr>
<tr>
<td>Integration Time</td>
<td>125 ms</td>
</tr>
<tr>
<td>Time Series Output Rate</td>
<td>8 Hz</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>40 dB</td>
</tr>
</tbody>
</table>

![Diagram of Beacon Receiver Hardware]

Ka-Band RF

- Ka-Band RF
- LNA +35 dB
- BPF 70 MHz
- IF Amp. +25 dB
- 70 MHz to 455 kHz Downconverter
- 455 kHz Output to ADC

Q-Band RF

- Q-Band RF
- LNA +35 dB
- BPF 20.2 GHz
- BPF 70 MHz
- IF
- 70 MHz to 455 kHz Downconverter
- Ref. LO 10 MHz
- 70 MHz to 455 kHz Downconverter
Beacon Receiver Software

**Basic FFT Approach**

- Frequency Resolution of $\frac{f_s}{N}$
- Error in Power Measurement (Scalloppping)

**Frequency Estimator Approach**

- Increased Frequency Resolution & Accuracy
- Increased Power Measurement Accuracy (No Scallopping)
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 $f_s$ 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

![Graph comparing FFT Peak and Frequency Estimator](image)
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-Nessel** – The same implementation as the Quinn-Fernandes method above, but modified to include optional optimization through *a priori* frequency information.
Simulated Frequency Estimate & Power

Frequency Estimate

Relative Power

+10dB SNR

-10dB SNR

-20dB SNR

Distance Between Bins

Distance Between Bins
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

Alphasat Measured IF Frequency (FFT)

Ka-Band
Q-Band

Alphasat Measured IF Frequency (Quinn-Fernandes)

Ka-Band
Q-Band
When compared to the expected doppler shift (derived from satellite position data), the beacon offset and drift can be estimated.
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

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  
flex.a.miranda@nasa.gov

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


