Institute for
Infocomm Research

I^{2}R

Technical Study Update on Space-based VHF Voice Communication System (Singapore)

FSMP WG/12
4 - 15 October 2021

Project Overview

Problem Statement:

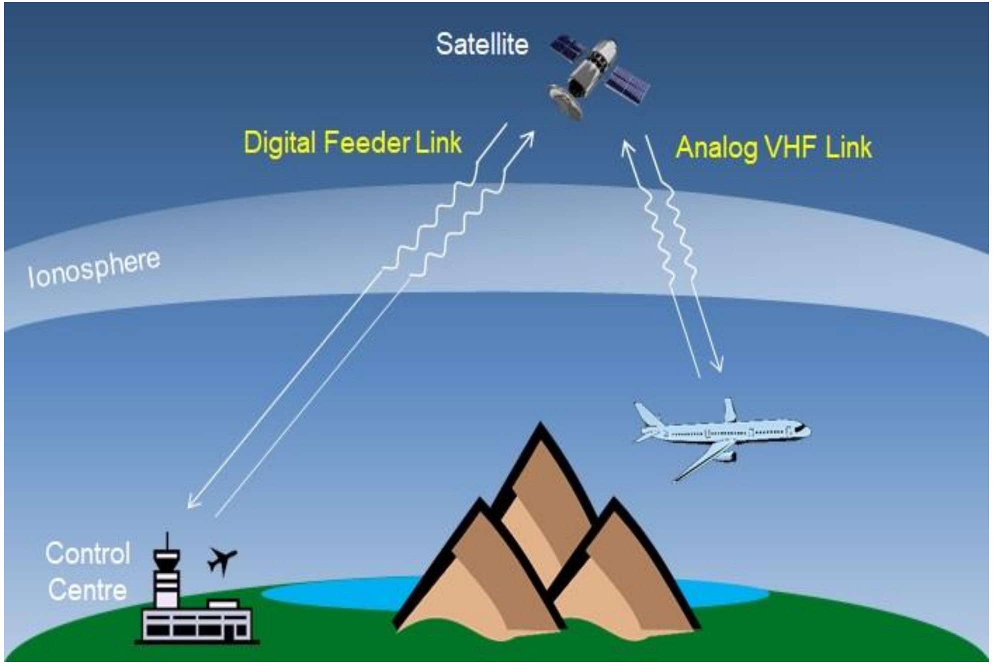
The existing VHF voice communication between the air traffic control officers and pilots is limited by line-of-sight and cannot cover oceanic areas beyond line-of-sight.

Objective:

To design a VHF voice communication solution based on satellite relay to overcome the line-of-sight limitation of existing system.

Project Duration:

1 year (1 Jul 2021 ~ 30 Jun 2022)

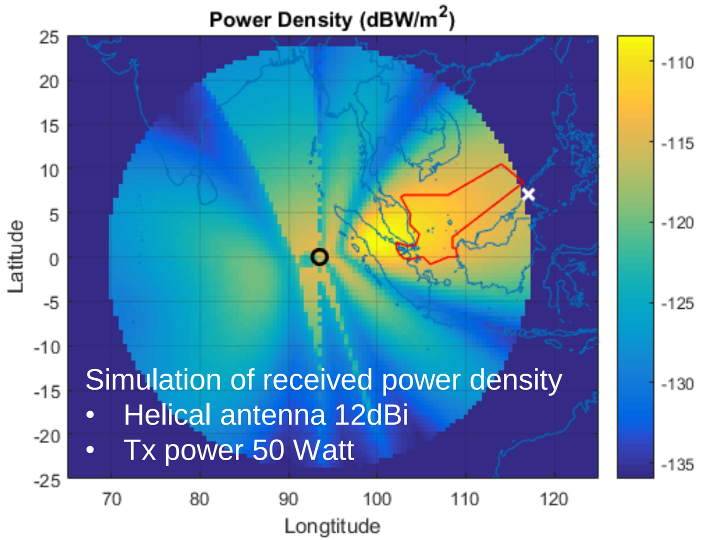


Project Scopes

- **Phenomenon Study**
  - **Scintillation Effect**: Investigate the time-varying irregularities of ionospheric electron density, model the propagation path of VHF signal and characterize the scintillation effects based on the real VHF signal recorded from existing satellite.
  - **Doppler Offset**: Analyse the Doppler offset caused by satellite motion and incorporate with the transmitter carrier offsets.
- **System Design**
  - **POC Satellite Payload Design & Space Deployment Study**:
    Conduct the top-level design of satellite payload (analog VHF link and digital feeder link) and study the space deployment scheme to provide high performance while minimizing the satellite weight/size.
  - **Processing Algorithm Design**:
    Develop the channel equalization and fusion processing algorithms to overcome the fading effects due to ionospheric scintillation; Develop the speech processing and enhancement algorithm to recover the contaminated voice signal.
- **Compatibility study of space-based VHF voice and existing services**
  - Study the compatibility of new space-based VHF voice communication system with existing primary services in band and in adjacent frequency bands to ensure the protection of existing primary services in accordance to the ITU Radio Regulation.

Technical Challenges for VHF Voice Link

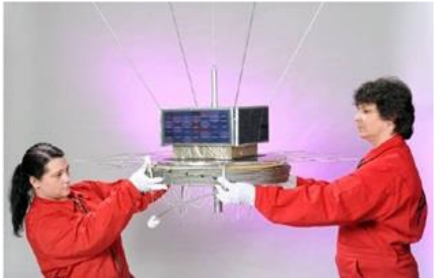
- Large satellite EIRP to meet the required power level at aircraft Rx (-116dBW/m^2, i.e., -90dBm for 0dB Rx gain)
- Deployable high gain VHF antenna (12-15dBi)
- Minimize signal spillage outside designated FIR
- Overcome the ionospheric scintillation effects
- Analysis of Doppler shift and Carrier offset



Simulation of received power density

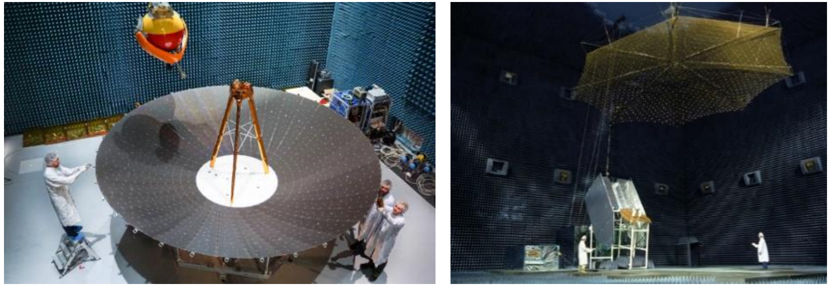
- Helical antenna 12dBi
- Tx power 50 Watt

Helical Antenna
(for illustration only)



Tom Sproewitz, et al, "Deployment verification of large CFRP helical high-gain antenna for AIS signals", 2011 IEEE Aerospace Conference, Big Sky, MT, USA, 5-12 March 2011

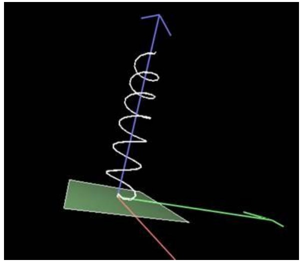
Parabolic Antenna
(for illustration only)

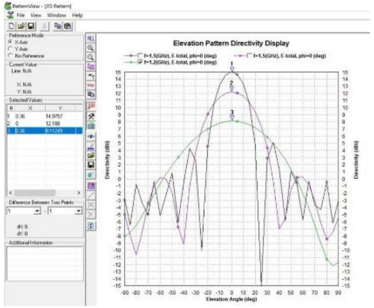


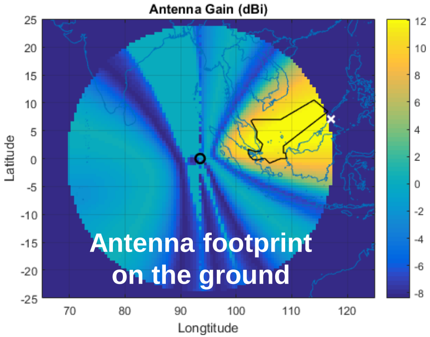
Power Density Distribution on the Ground

Assumption:

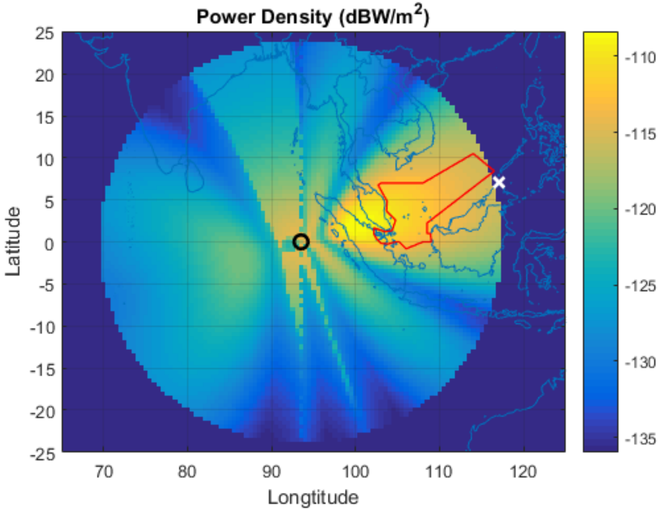
- Helical antenna 12dBi
- Tx power 50 Watt

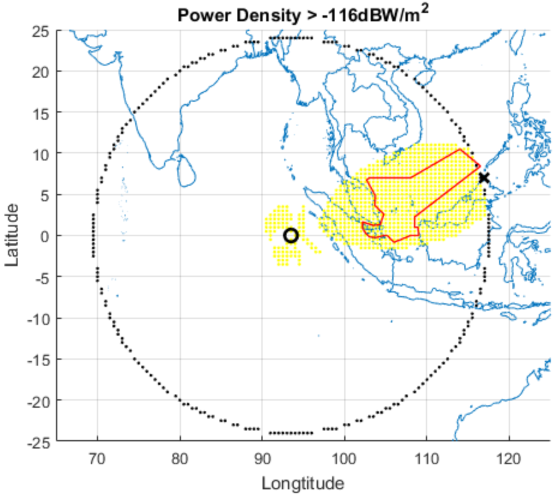






Antenna footprint on the ground





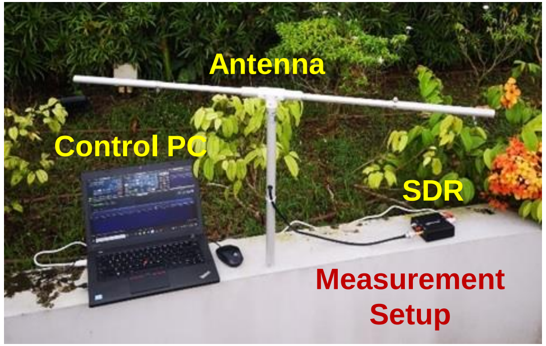
More simulations will be done based on the new design of antenna patterns.

Scintillation Effects

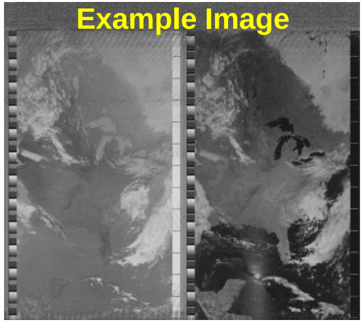
Analysis of Scintillation with Available VHF Satellite Signals

Frequency	137 MHz – 138 MHz (Downlink)
Modulation	Symmetric Differential Phase Shift Keying
Bandwidth	15 kHz
Service	IoT, M2M messaging

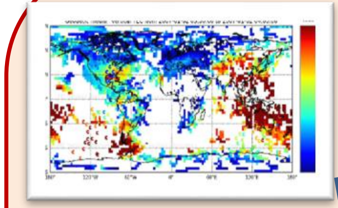
Can be used to extract the amplitude / phase parameters caused by scintillation fading!



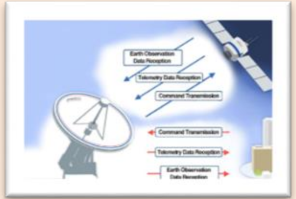
Frequency	137.1 MHz – 137.9125 MHz
Modulation	FM carrier AM sub-carrier
Bandwidth	34 kHz
Service	Weather information in APT format



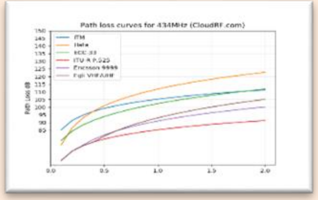
Approach for Scintillation Study



Ionospheric Phenomenon Study

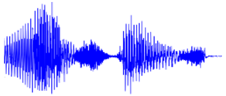


Experimental Analysis using ORBCOMM / NOAA Signal



VHF Propagation Modelling

Phenomenon Study

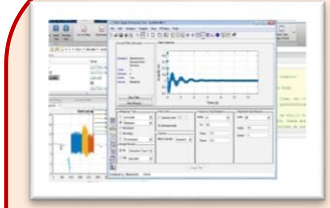


Ideal VHF Voice Signal

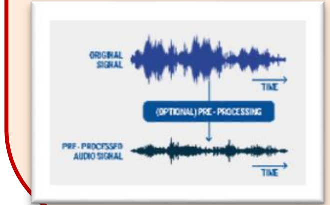
Scintillation Fading

⊕

Synthesized VHF Voice Signal



Channel Equalization



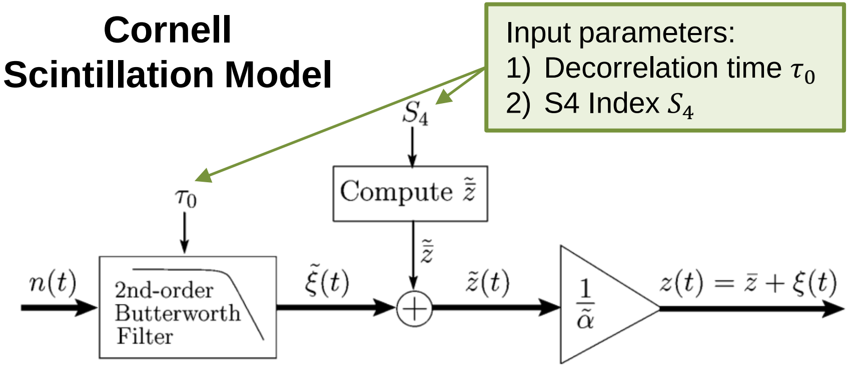
AI-based Speech Processing

Enhanced Voice Signal

Algorithm Study

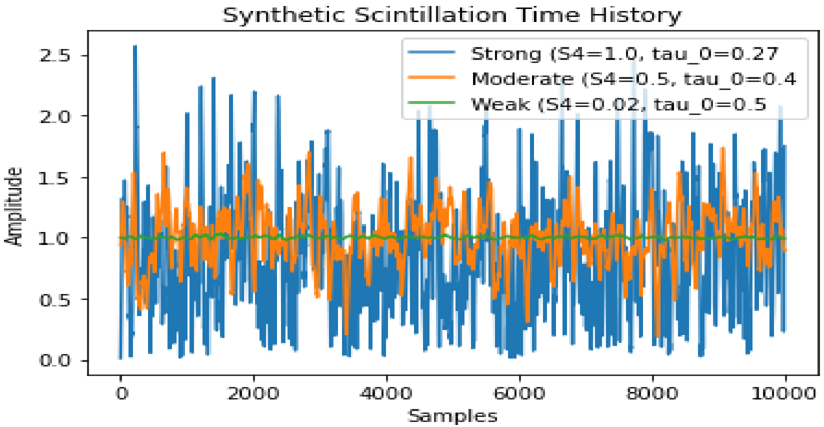
Voice Signals with Synthetic Scintillation

Cornell Scintillation Model



Input parameters:
1) Decorrelation time τ_0
2) S4 Index S_4

Todd E. Humphreys, et al, “Simulating ionosphere-induced scintillation for testing GPS receiver phase tracking loops,” IEEE Journal of Selected Topics in Signal Processing, vol.3, no.4, August 2009, pp.707-715.



ChangiTower.wav

Original.wav

Weak Scintillation.wav

Moderate Scintillation.wav

Strong Scintillation.wav

Channel3.wav

Original.wav

Weak Scintillation.wav

Moderate Scintillation.wav

Strong Scintillation.wav

ORBCOMM and NOAA Signals with Simulated Scintillation Effects

ORBCOMM Signals with Scintillation (1/2)

Frequency	137 MHz – 138 MHz (Downlink)
Modulation	Symmetric Differential Phase Shift Keying
Bandwidth	15 kHz
Service	IoT, M2M messaging

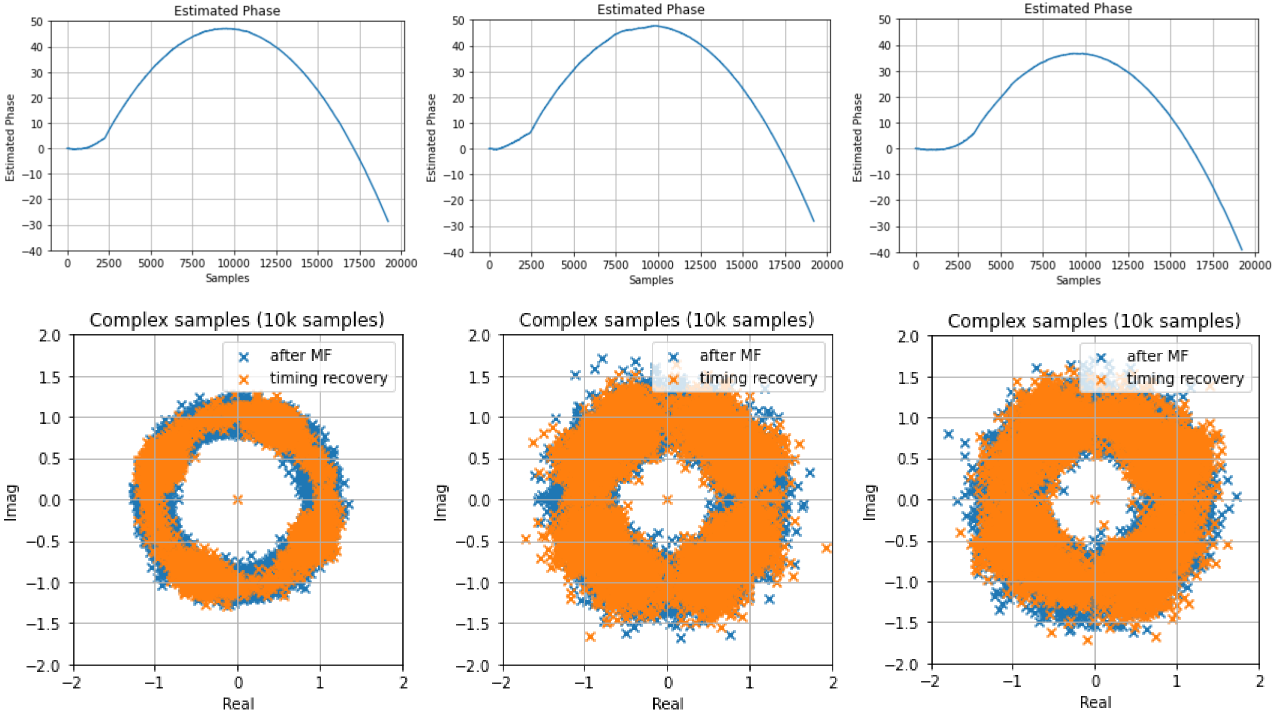
- ORBCOMM signals are corrupted with scintillation effects generated from the Cornell Scintillation Model.
- Complex scintillation effects corresponding to S4 Index 0.5 (moderate case) & 0.8 (strong case) were used.
- The original ORBCOMM signal has a PER = 3%.
- Surprisingly, even with the scintillation effects added, the PER remains at 3%!
- This is because:
  1. The decoder has its own phase and frequency offset estimation, which is able to compensate for the scintillation effects.
  2. The data is differentially encoded.

```
List of packets: (### indicates checksum failed)

### Unrecognized packet: 8F5E8C1A5E354CE775C6A33E

Fill: data: 6FE4A5F1DDC8B12CADE5

Fill: data: 567DC3683187453D728D

Fill: data: 463E5D5FB36A15E68001

Message: msg_packet_num: 0 msg_total_length: 2 data: C06985EC05B0E108E3

Message: msg_packet_num: 1 msg_total_length: 2 data: 506883481280AC82E1

Message: msg_packet_num: 0 msg_total_length: 3 data: C15284322C589600E3

Message: msg_packet_num: 1 msg_total_length: 3 data: 618A01A94750081F49

                                    ⋮

### Unrecognized packet: 1401091E10010200030105F1

### Unrecognized packet: 5A696B000000000000002267

Fill: data: 62D0CF10E6C6EB5B4129

Fill: data: 8F08F3CC94BFC8389881

Fill: data: 3CCE1007D74EF60AD937

Fill: data: DAB7BAFDC2BB293DF78C

                                    ⋮

3 packets with errors, 0 packets corrected, PER:   3.0%
```

CREATING GROWTH, ENHANCING LIVES

ORBCOMM Signals with Scintillation (2/2)

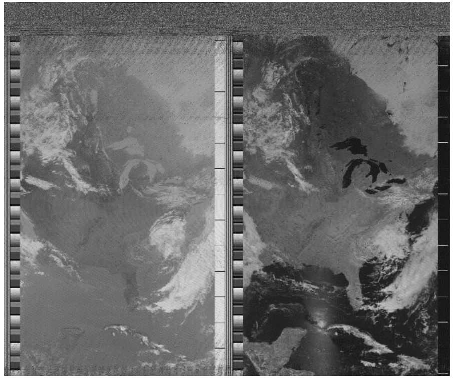
Original | S4 Index = 0.5 | S4 Index = 0.8

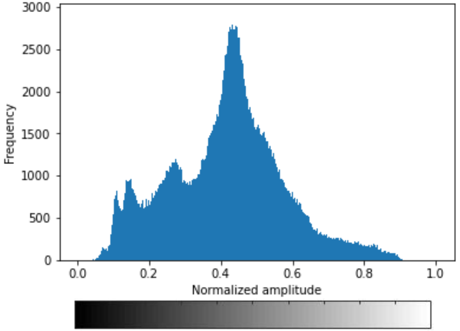


- The phase estimation is able to compensate the phase offset caused by the scintillation and track the frequency offset too.
- The distribution of the demodulated signal after compensation and recovery deteriorates with scintillation.
- However, due to differential coding, the impact on the PER is not significant.

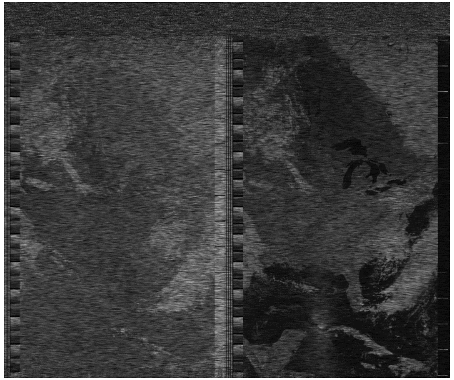
NOAA Signals with Scintillation – Example 1

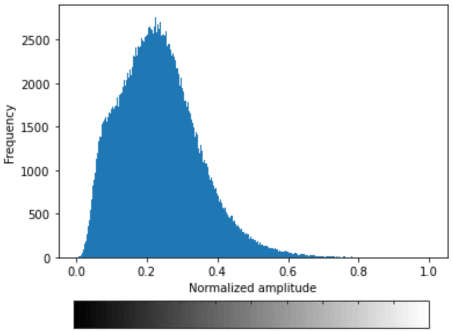
Original



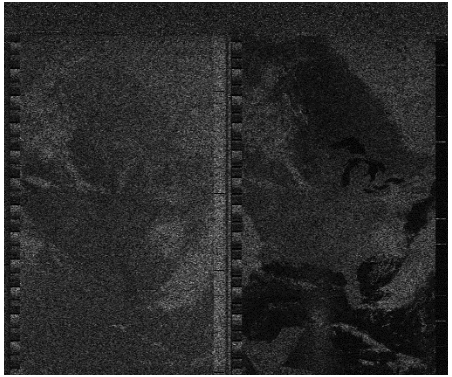


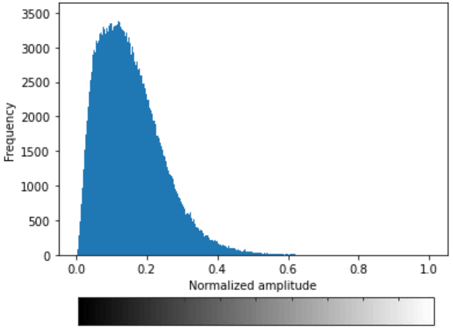
S4 index = 0.5





S4 Index = 0.8



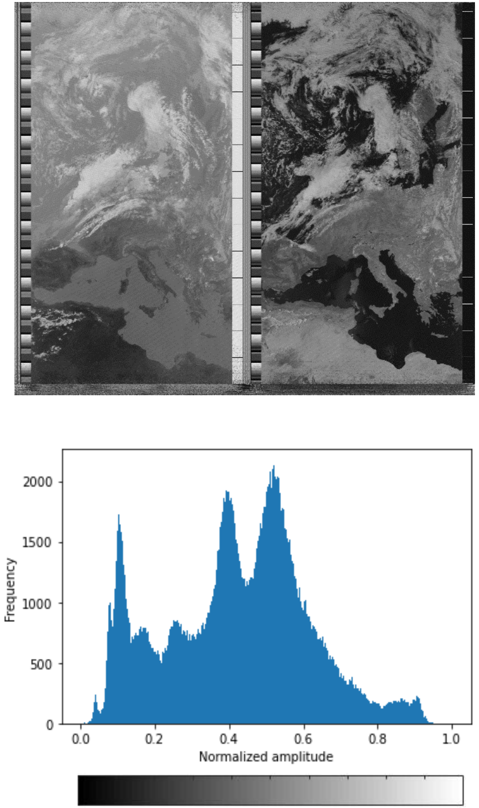


Frequency	137.1 – 137.9125 MHz
Modulation	AM
Bandwidth	34 kHz
Service	Weather images

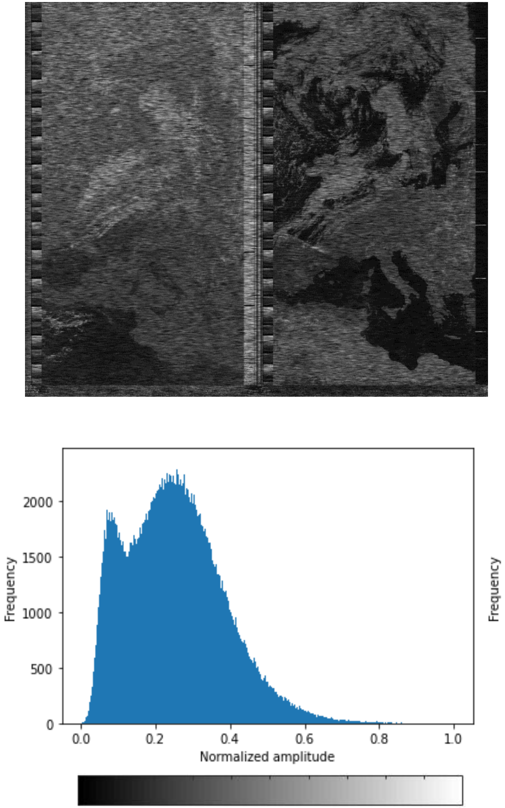
Due to scintillation, the samples are skewed towards the low-amplitude region, thus causing the image to appear darker and noisy.

NOAA Signals with Scintillation – Example 2

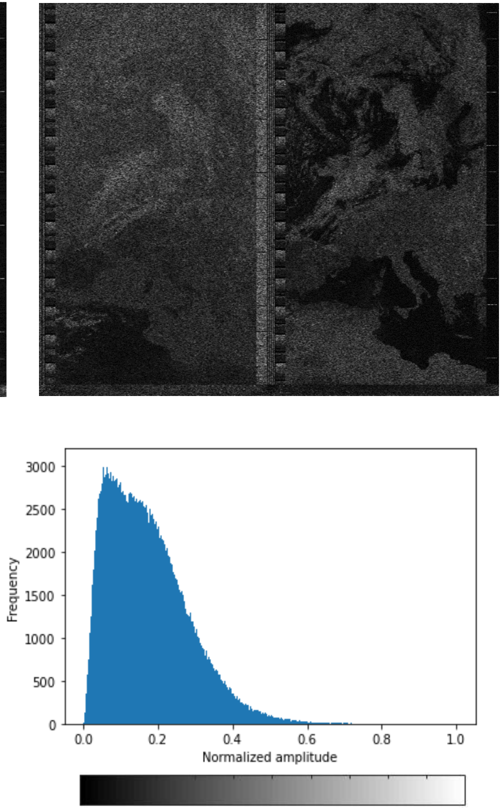
Original



S4 index = 0.5



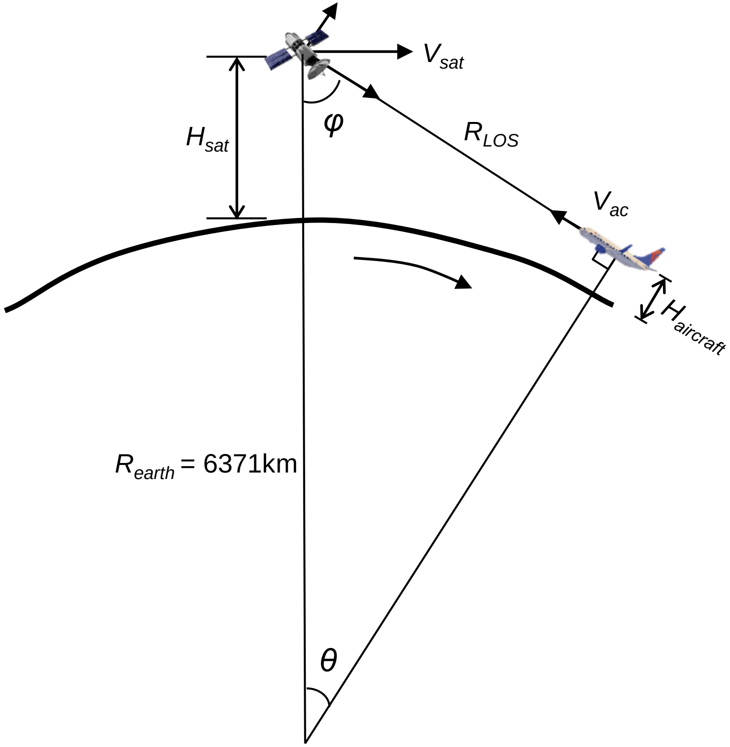
S4 Index = 0.8



Similar observation as in Example 1.

Doppler Shift

Maximum Doppler Shift



$$R_{LOS} = \sqrt{(R_{earth} + H_{sat})^2 + (R_{earth} + H_{aircraft})^2}$$

$$\theta = \cos^{-1}\left(\frac{R_{earth}+H_{aircraft}}{R_{earth}+H_{sat}}\right) \qquad \varphi = \sin^{-1}\left(\frac{R_{earth}+H_{aircraft}}{R_{earth}+H_{sat}}\right)$$

$$V_{sat} = \sqrt{\frac{G \cdot M}{(R_{earth} + H_{sat})}}$$

where $G = 6.6743e^{-11}$ m^3·kg^{-1}·s^{-2} is the gravitational constant
$M = 5.972e^{24}$ kg is the mass of earth

When the satellite flies along equatorial orbit and towards the same direction as the earth rotation, the linear velocity of earth rotation should be deducted from the satellite velocity V_{sat}.

$$V'_{sat} = V_{sat} - \omega_{earth}(R_{earth} + H_{sat})$$

When the aircraft flies towards the satellite (i.e., the worst case), the Doppler between satellite and aircraft is.

$$Doppler = \frac{f_0}{c}\left(V'_{sat}\sin\varphi + V_{aircraft}\right)$$

Maximum Doppler Shift

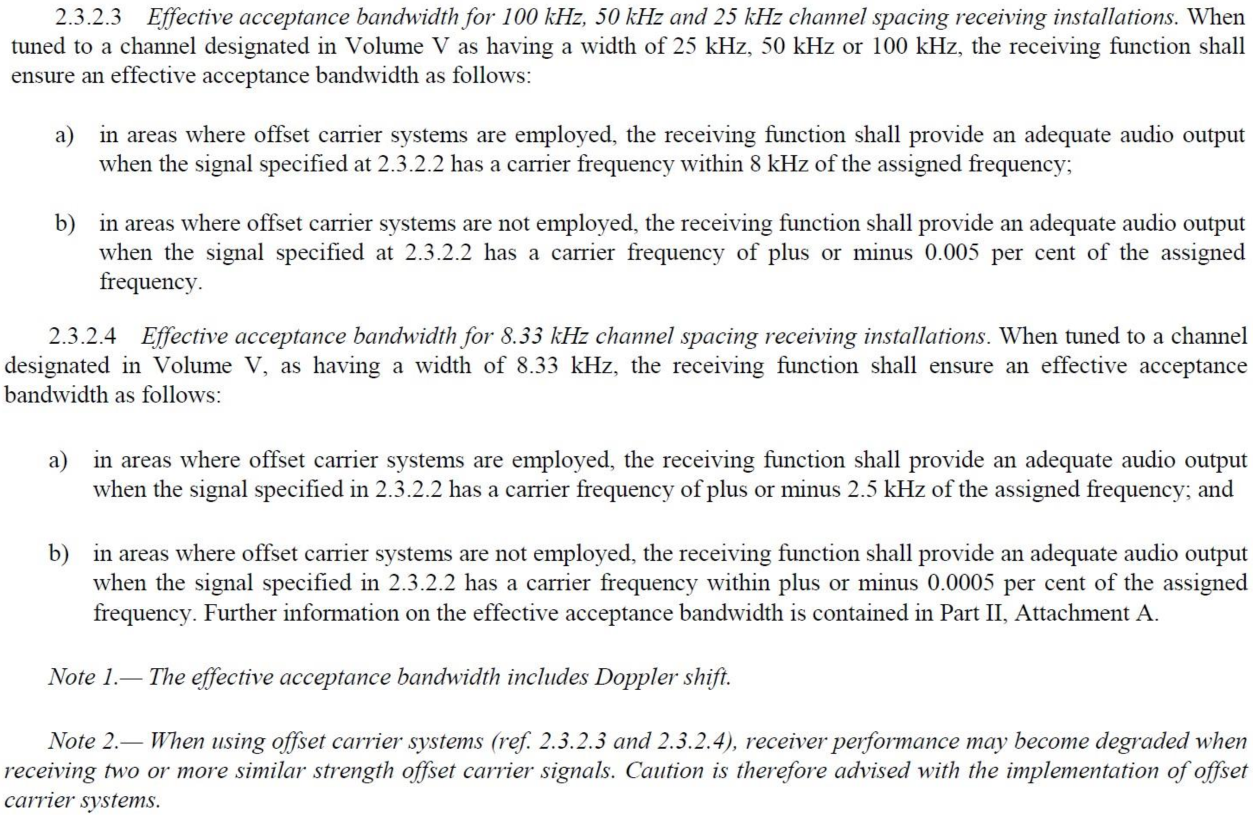
When f_0=137MHz, $H_{aircraft}$=10km

	Max Doppler due to aircraft movement	Total Doppler with SAT Attitude = 300 km VLEO	Total Doppler with SAT Attitude = 600 km LEO	Total Doppler with SAT Attitude = 1200 km LEO
Aircraft speed = 1000 km/h	127 Hz	3.29 kHz	3.08 kHz	2.71 kHz
Aircraft speed = 1500 km/h	190 Hz	3.35 kHz	3.14 kHz	2.77 kHz
Aircraft speed = 2000 km/h	254 Hz	3.42 kHz	3.20 kHz	2.83 kHz

- The aircraft height $H_{aircraft}$ has little effect on the Doppler. For example, when H_{sat} = 600km and $V_{aircraft}$ = 1000km/h, the total Doppler is **3.08kHz** for $H_{aircraft}$ =20km and **3.07kHz** for $H_{aircraft}$ =0km.
- These results are valid for circular equatorial orbit, and we can make use of the earth rotation to reduce the Doppler. For other circular orbits with inclination angles, the Doppler will be slightly larger. For example, when H_{sat} = 600km and $V_{aircraft}$ = 1000km/h, the total Doppler is **3.08kHz** for equatorial orbit and up to **3.29kHz** for polar orbit (worse case, inclination angle = 90º).
- This Doppler frequency is on top of the satellite transmit signal stability (e.g., ±0.5kHz).

Permissible Error in Aircraft VHF Receiver

ICAO Aeronautical Telecommunications Annex 10 Volume III (2nd Edition, July 2007), Section 2.3 “System Characteristics of the Airborne Installation”



2.3.2.3 *Effective acceptance bandwidth for 100 kHz, 50 kHz and 25 kHz channel spacing receiving installations.* When tuned to a channel designated in Volume V as having a width of 25 kHz, 50 kHz or 100 kHz, the receiving function shall ensure an effective acceptance bandwidth as follows:

a) in areas where offset carrier systems are employed, the receiving function shall provide an adequate audio output when the signal specified at 2.3.2.2 has a carrier frequency within 8 kHz of the assigned frequency;

b) in areas where offset carrier systems are not employed, the receiving function shall provide an adequate audio output when the signal specified at 2.3.2.2 has a carrier frequency of plus or minus 0.005 per cent of the assigned frequency.

2.3.2.4 *Effective acceptance bandwidth for 8.33 kHz channel spacing receiving installations*. When tuned to a channel designated in Volume V, as having a width of 8.33 kHz, the receiving function shall ensure an effective acceptance bandwidth as follows:

a) in areas where offset carrier systems are employed, the receiving function shall provide an adequate audio output when the signal specified in 2.3.2.2 has a carrier frequency of plus or minus 2.5 kHz of the assigned frequency; and

b) in areas where offset carrier systems are not employed, the receiving function shall provide an adequate audio output when the signal specified in 2.3.2.2 has a carrier frequency within plus or minus 0.0005 per cent of the assigned frequency. Further information on the effective acceptance bandwidth is contained in Part II, Attachment A.

Note 1.— The effective acceptance bandwidth includes Doppler shift.

Note 2.— When using offset carrier systems (ref. 2.3.2.3 and 2.3.2.4), receiver performance may become degraded when receiving two or more similar strength offset carrier signals. Caution is therefore advised with the implementation of offset carrier systems.

Permissible Error in Aircraft VHF Receiver

In areas where offset carrier systems are **not** employed

- For 25kHz channel spacing, “the receiving function shall provide an adequate audio output when the signal specified at 2.3.2.2 has a carrier frequency of plus or minus **0.005 per cent** of the assigned frequency.”
  - for a channel at 118MHz, 0.005%*118MHz = ±**5.9kHz**
  - for a channel at 136MHz, 0.005%*136MHz = ±**6.8kHz**

Doppler shifts are within the permissible bandwidth of aircraft receiver.

- For 8.33kHz channel spacing, “the receiving function shall provide an adequate audio output when the signal specified at 2.3.2.2 has a carrier frequency of plus or minus **0.0005 per cent** of the assigned frequency.”
  - for a channel at 118MHz, 0.0005%*118MHz = ±**0.59kHz**
  - for a channel at 136MHz, 0.0005%*136MHz = ±**0.68kHz**

Doppler shifts may exceed the permissible bandwidth of aircraft receiver, and must be reduced.

In areas where offset carrier systems are employed

- For 25kHz channel spacing, “the receiving function shall provide an adequate audio output when the signal specified at 2.3.2.2 has a carrier frequency **within 8kHz** of the assigned frequency.”
- For 8.33kHz channel spacing, “the receiving function shall provide an adequate audio output when the signal specified in 2.3.2.2 has a carrier frequency of **plus or minus 2.5kHz** of the assigned frequency.”

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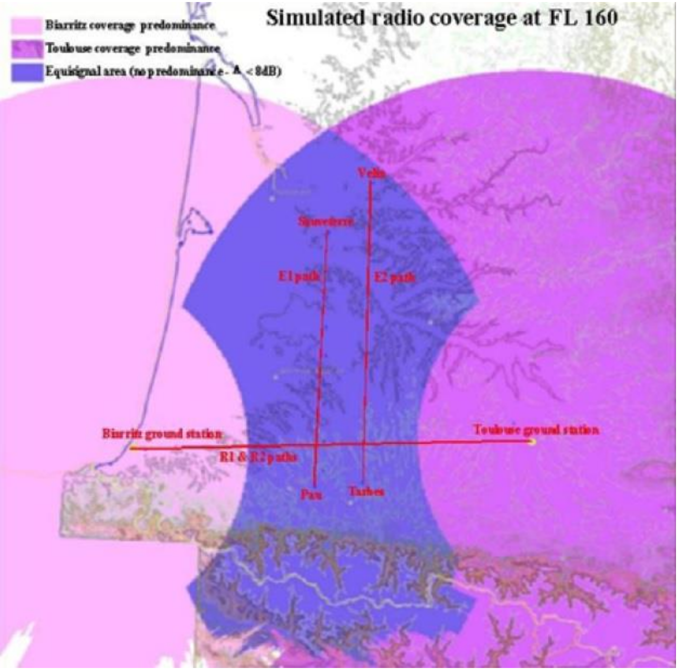
Carrier Offset

Carrier Offset

- To minimize frequency usage, multiple terrestrial VHF stations may transmit simultaneously at the same frequency channel. Thus, the aircraft may receive the signals from multiple VHF stations.
- Due to the signal stability of different VHF stations and/or Doppler offsets caused by aircraft motion, the carriers of signals received by the aircraft may differ from each other (~ a few hundreds Hz). The intermodulation of signals from different VHF stations may generate the cross-terms falling into the voice frequency band, and therefore significantly degrade the voice quality after demodulation.
- To overcome this effect, a set of carrier offsets can be applied to the VHF stations when they need to transmit at the same frequency band.



CLIMAX/8.33: To extend 8.33 kHz benefits

Carrier Offset

$$\cos\alpha + \cos\beta = 2\cos\frac{\alpha+\beta}{2}\cos\frac{\alpha-\beta}{2}$$

Assuming 2 VHF stations transmit at 130MHz simultaneously, and the voice content is 1kHz cosine signal.

Scenario 1 (ideal case):

Station 1: f_c = 130MHz

Station 2: f_c = 130MHz

Scenario 2 (w/o carrier offset):

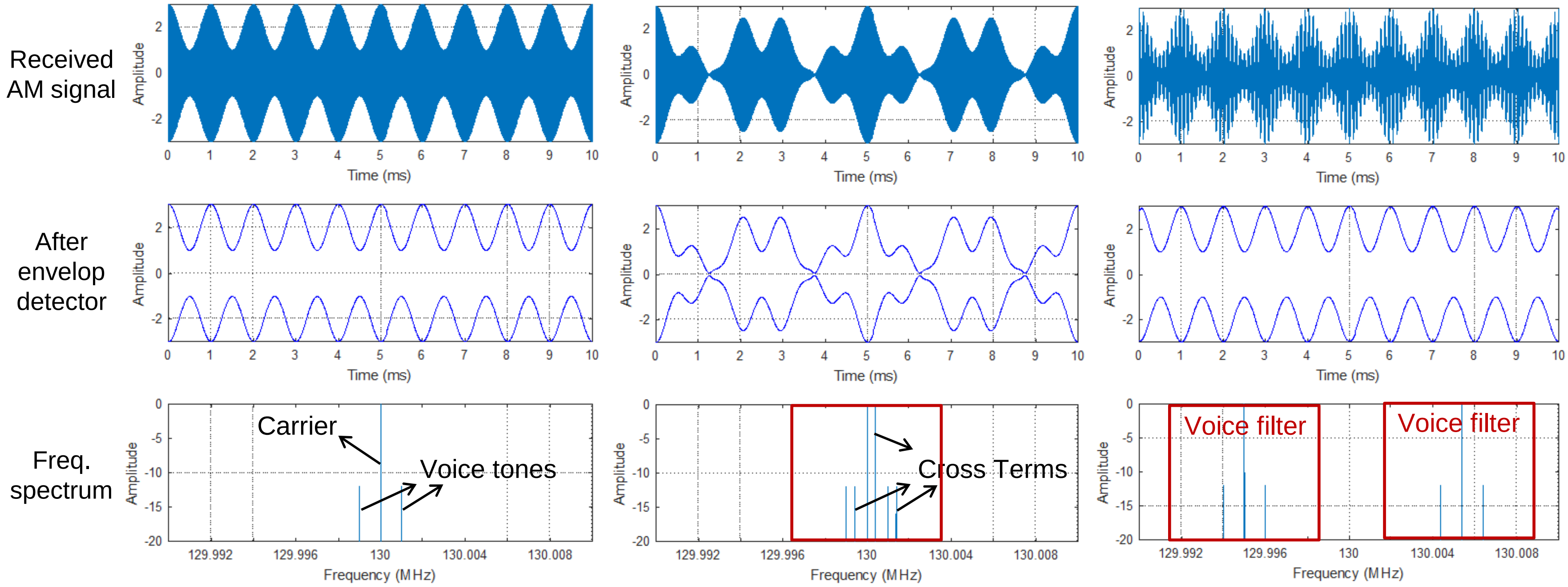
Station 1: f_c = 130MHz - 68Hz

Station 2: f_c = 130MHz + 332Hz

Scenario 3 (with carrier offset):

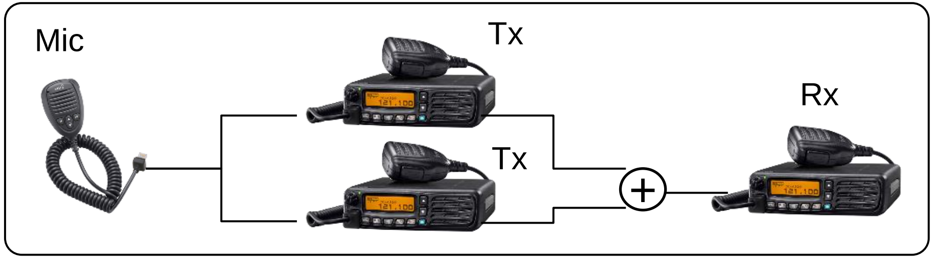
Station 1: f_c = 130MHz - **5kHz** - 68Hz

Station 2: f_c = 130MHz + **5kHz** + 332Hz

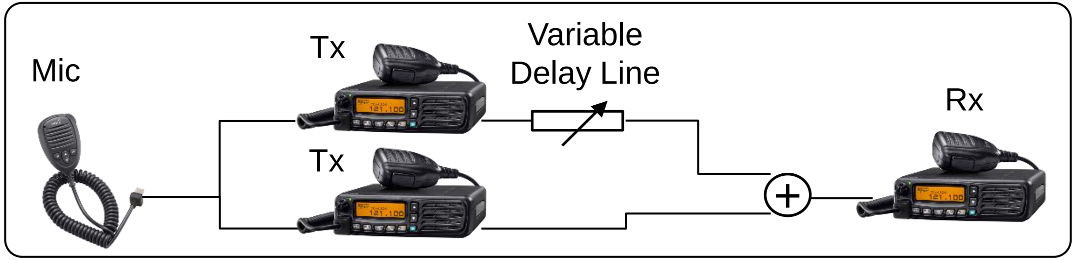


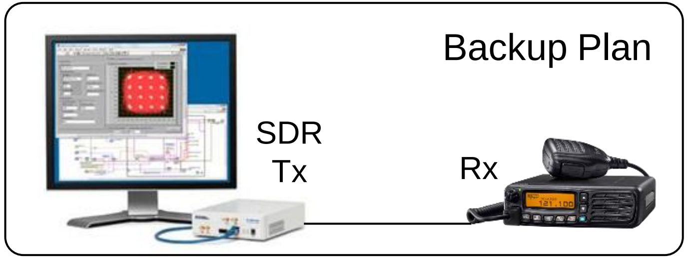
Lab experiment for Simultaneous Transmissions from Multiple Stations

- To analyse the effects of **carrier offset** on the received voice quality



- To analyse the effects of **different path delay** on the received voice quality





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