

# Recreating the effects of Artificial Ionospheric Modification observed in the HF environment; an application of numerical ray tracing

Natasha Jackson-Booth<sup>1</sup>, Luke Selzer<sup>1</sup>, Ronald Caton<sup>2</sup>, Todd Pedersen<sup>2</sup>, Richard Penney<sup>1</sup>, Joseph Reid<sup>1</sup>, Paul Cannon<sup>3</sup>, Keith Groves<sup>4</sup>, Matthew Angling<sup>3</sup>, Gemma Attrill<sup>5</sup>, Richard Parris<sup>2</sup> and Yi-Jiun Su<sup>2</sup>

<sup>1</sup> QinetiQ  
Malvern, Worcs, WR14 3PS  
UK

<sup>2</sup> Air Force Research Laboratory, Space Vehicles Directorate  
Kirtland AFB, NM  
USA

<sup>3</sup> University of Birmingham  
Birmingham, B15 2TT  
UK

<sup>4</sup> Boston College, Institute for Scientific Research,  
Chestnut Hill, MA  
USA

<sup>5</sup> Defence Science and Technology Laboratory  
Porton Down, Salisbury, SP4 0JQ  
UK

## ABSTRACT

Artificial Ionospheric Modification (AIM) can occur through injections of aerosols, chemicals or radio (RF) signals into the ionosphere. The Metal Oxide Space Clouds (MOSC) experiment was undertaken in April/May 2013 to investigate chemical AIM. Two sounding rockets were launched from Kwajalein Atoll (part of the Marshall Islands) and each released a cloud of vaporized samarium (Sm). The samarium created a localized plasma cloud that formed an additional ionospheric layer.

The effects were measured by a wide range of ground based instrumentation dispersed in several locations across the Marshall Islands. The collected data included HF measurements, optical observations, trans-ionospheric beacon measurements, and incoherent scatter measurements using the ALTAIR radar. A subset of the HF measurements included a 17 channel direction finding chirp receiver, which was used to observe and track the cloud. The recorded ionograms showed that the new layer was visible for approximately 25 minutes after release: the maximum frequency of the new trace decays with time, indicating a decrease in cloud density. The ionograms also revealed the existence of ‘ghost traces’ above the F-layer.

Extending this work, a parametric cloud model was developed by AFRL using optical data. The cloud model was added to simulated ionospheric electron density grids to understand the impact on radio propagation in the cloud’s vicinity. A 3D numerical ray trace was undertaken to find the paths through the electron density grid for a given fan of elevation and azimuth firing angles. Synthetic ionograms were then produced using the ratio of ray path length to speed of light as an estimation of the delay between transmission and observation for a given frequency of radio wave. This process was iterated over frequencies ranging from 2 to 30 MHz to build the ionograms.

A possible explanation for the ‘ghost traces’ has been found whereby the ray path is deflected from the cloud to the F layer and down to the receiver. In certain geometries this small deviation adds enough delay to represent it as a distinct layer. This result is consistent with the angle of arrival information obtained from the deployed HF system.

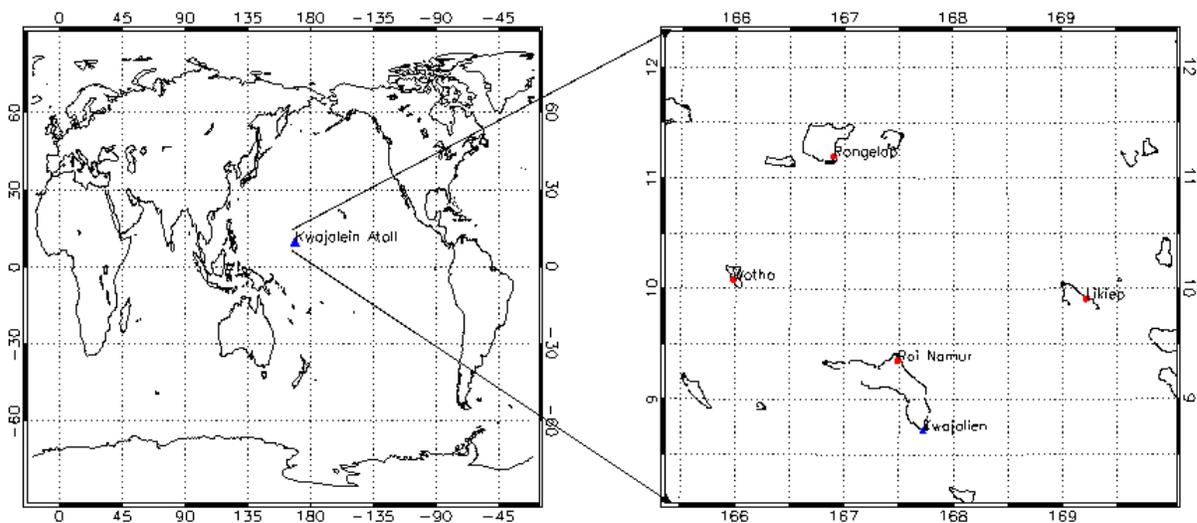
## 1. INTRODUCTION

Artificial Ionospheric Modification (AIM) can occur through injections of aerosols, chemicals or radio frequency (RF) signals into the ionosphere. The Metal Oxide Space Clouds (MOSC) experiment was conducted in April/May 2013 to investigate chemical AIM [Caton *et al.*, 2014].

Two sounding rockets were launched by NASA from the US Reagan Test Facility on the Kwajalein Atoll in the Pacific Ocean (part of the Marshall Islands, 9.395°N, 167.469°E, Figure 1). Each rocket carried a payload of two samarium (Sm) canisters, which released a cloud of vaporized Sm that created a localized plasma cloud. The experiment was designed to investigate:

- The production of controlled increases in ionospheric density to mitigate and/or control scintillation
- On-demand space plasma generation (e.g. to modify HF propagation)

The effects were measured by a wide range of ground based instrumentation dispersed in several locations across the Marshall Islands. The instrumentation included optical observations, trans-ionospheric beacon measurements, and incoherent scatter measurements using the ALTAIR radar. This paper describes initial results from a sub-set of the ground based high frequency (HF, 2-30 MHz) ionospheric sounders that were also deployed.



**Figure 1:** Map of the Marshall Islands. The blue triangle on the right hand map is the location of the UK receiver array NIRIS.

A subset of the HF observations included data collected using a 17 channel direction finding chirp receiver called NIRIS [Jackson—Booth *et al.*, 2012]. NIRIS was used to observe and track the cloud as it evolved. Preliminary analysis using the NIRIS data set showed that the two releases of samarium each produced a thin new ionospheric layer. The new layer was detected on the ionograms and extended to a maximum frequency of approximately 10 MHz. It decayed over ten minutes on the Likiep to Kwajalein path and over thirty-five minutes on the Rongelap to Kwajalein path [Jackson-Booth *et al.*, 2014].

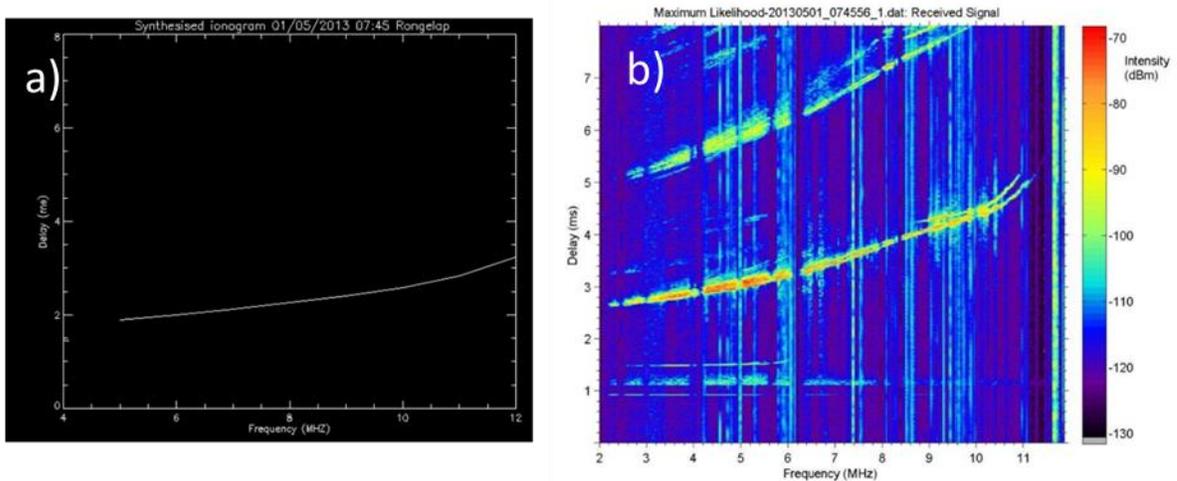
During the initial analysis of the Likiep to Wotho path by Boston College a trace was seen just above the F-layer on ionograms [Groves, 2013]. Their existence was independently confirmed on the NIRIS ionograms recorded on the Rongelap to Kwajalein path.

This paper has extended the work previously reported by ray tracing through an electron density grid, which incorporates a parametric cloud model developed by AFRL using optical data. Synthetic ionograms were then produced using the ratio of ray path length to speed of light as an estimation of the delay between transmission and observation for a given frequency of radio wave. This process was iterated over frequencies ranging from 2 to 30 MHz to build the ionograms.

## 2. Ray tracing

In order to understand the ionospheric impact of the samarium release a perturbation model was developed for the ionosphere during the MOSC launch. The model comprised a background ionosphere and a model of the cloud, produced by AFRL. Ray tracing was then undertaken to understand the full effects of a samarium release on RF propagation.

The initial work used the International Reference Ionosphere (IRI) model as the background ionosphere. It was run for the correct time with monthly input parameters (e.g. sunspot number). However, it was found that IRI was not producing ionograms consistent with those recorded on NIRIS, with the F-trace occurring at a lower delay than on the recorded ionograms. Figure 2a shows a synthesised ionogram produced by ray tracing through a background ionosphere modelled by IRI alongside Figure 2b, an ionogram recorded by NIRIS, both for the Rongelap to Kwajalein path. It can be seen that the F-trace of the synthesised ionogram occurs between 2 and 3.2 ms (for frequencies 5 – 11 MHz) compared to 3 and 4.6 ms (for the same frequency range) on the recorded ionogram.



**Figure 2:** Synthesized and recorded ionograms from 07:45 UT on Rongelap to Kwajalein path: a) A synthesized ionogram using IRI as the background ionosphere with the F layer occurring at delays between 1.8 ms and 3.2 ms; b) an ionogram recorded on NIRIS showing the F-layer occurring between delays of 2.6 ms and 5 ms. Note there is a different frequency extent in the two plots.

A key disadvantage of using IRI as a background model is that the only driving parameter is sunspot number. This makes it very hard to easily tune the background ionosphere to match observation, especially whilst keeping the sunspot number realistic. To improve the background ionospheric model a Chapman layer [Chapman, 1931] was used instead of IRI. A Chapman layer is defined as:

$$N = N_0 \cdot \exp\left(\frac{1}{2}[1 - z - \exp(-z)]\right) \quad \text{Equation 1}$$

Where,  $N_0$  is the maximum electron density (defined as  $1.4 \cdot 10^{12} \text{ e}^-/\text{m}^3$ ) and  $z$  is:

$$z = \frac{(h-h_0)}{H} \quad \text{Equation 2}$$

Where,  $h_0$  is the height of the layer peak and  $H$  is the scale height.

Using a Chapman layer makes it possible to adjust the position of the layer through modifying scale height and layer height. Based on the data available through the forward oblique ionograms recorded by NIRIS and the Digisonde,  $H$  was defined to be 60 km and a F-layer height of 400km was used.

A parametric model developed by AFRL was then incorporated in the background ionospheric model to recreate experimental results from the MOSC experiment. In this model the cloud's density evolves in space and time as the cloud is dispersed by atmospheric motion and diffusion processes. It is assumed that the centroid altitude remains consistent throughout the experiment while latitude and longitude values drift.

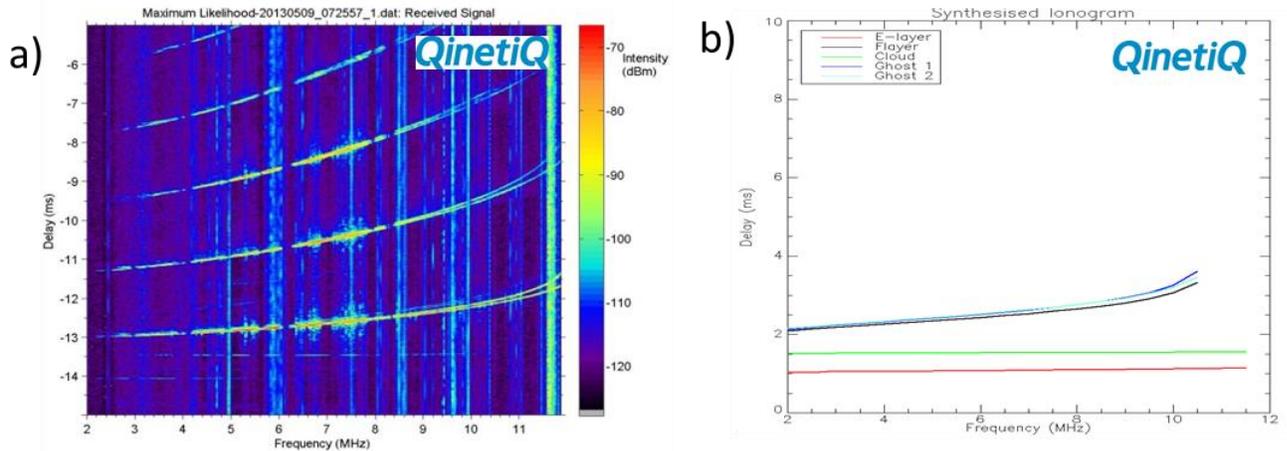
Ray paths were reconstructed using a Runge – Kutta – Felhberg (RKF) solver algorithm [Press *et al.*, 1992] to numerically solve radio propagation equations for various frequencies through the electron density grid for a given fan of elevation and azimuth firing angles. Ionograms were then produced using the ratio of ray path length to the speed of light as an estimation of the delay between transmission and observation for a given frequency of radio wave.

### 3. RESULTS

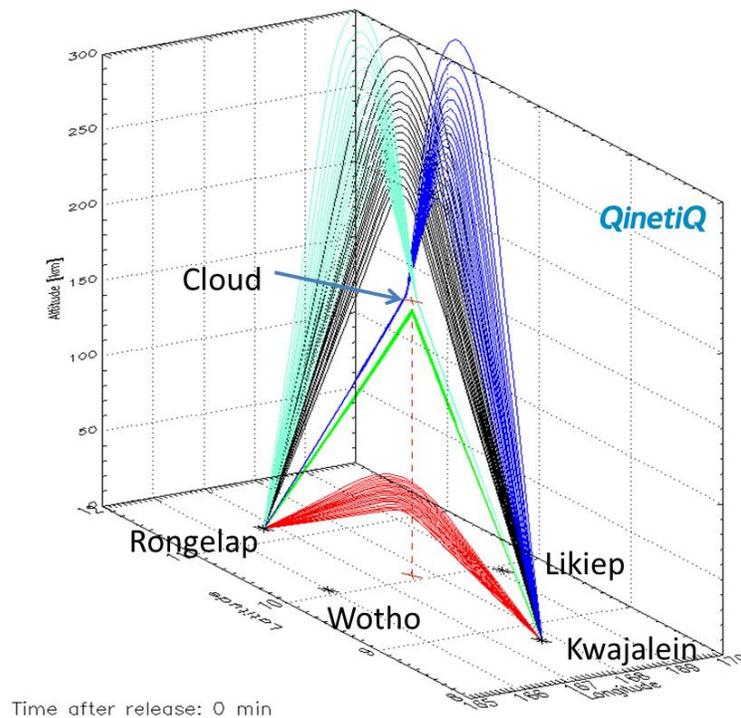
The chirp transmissions recorded by NIRIS were used to generate ionograms; i.e. plots of frequency versus group delay for the ionospheric returns. Ionograms were recorded at 5 minute intervals throughout the MOSC experiment with the aim of understanding the impact of the cloud disturbance on the ionosphere. Previous reported results [Jackson-Booth *et al.*, 2014] showed that the new trace remained visible on the ionograms for approximately twenty five minutes; however, the maximum usable frequency (MUF) of the artificial layer dropped during that time to 2.4 MHz.

Here we present ionograms synthesized from ray tracing through a background ionosphere containing a cloud along with their experimentally observed counterparts, for the second release (07:25:58 UT on the 9th May 2013). The parameters we will focus on are the delay times and the frequency range of layers formed due to the presence of the cloud. The ionogram recorded on NIRIS immediately after release for the Rongelap to Kwajalein path is shown in Figure 3a. It shows the F and E layers as well as a cloud return and a faint 'Ghost trace' just above the F layer induced trace. The synthesized ionogram of the Rongelap to Kwajalein path is shown in Figure 3b for two minutes after release (e.g. 07:27:58 UT). This path is used as a canonical example for all receiver – transmitter geometries which display similar properties in the presence of the cloud, unless stated otherwise. The synthesized ionograms showed strong agreement with the experimentally obtained

ionograms with the exception of the E layer return. This can be easily explained due to an overestimation of the E layer density in the Chapman layer used to simulate the E layer.



**Figure 3:** a) Ionogram recorded on NIRIS for the Rongelap to Kwajalein path (stat of sweep 07:26:04 UT on May 9th 2013, sweep rate of 100 kHz/s). The E layer and multiple F hops are visible. The new layer can be seen at approximately -13.5 ms and two secondary new layers sitting above the 1 hop F layer bounce. (Note delays are offset by -15 ms). b) The synthesized ionogram of the Rongelap to Kwajalein path is presented for two minutes after release. The simulation was completed using a Chapman layer for both the E and F layers with the superposition of the AFRL Cloud model. The layers due to the presence of the cloud are shown in green and blue and are seen to span 2.0 – 11.5 MHz for the Cloud reflection and 2.0 – 10.5 MHz for the two Ghost rays.



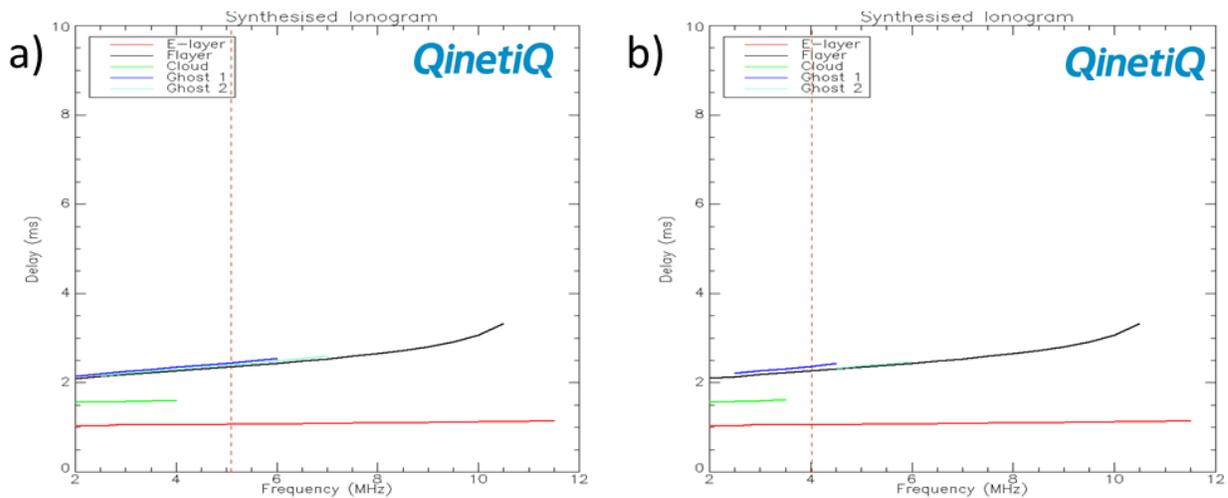
**Figure 4:** The geometry of the ray paths is shown in a three dimensional ray trace output for transmissions from a transmitter at Rongelap to a receiver at Kwajalein. The black traces show the rays which have undergone a 1 hop F layer reflection. The red traces similarly show a 1 hop E layer reflection. The green traces show reflections off of the cloud while the two blue trace sets show the Ghost paths. As can be seen by the ray paths the simulations clearly predict that there will be an interaction with the cloud. This plot was made using the AFRL cloud model immediately after release for a frequency range of 2-15 MHz.

In the presence of the cloud we see a return of radio signal manifested as new layers not previously seen in E and F layer reflection paths. Ray paths corresponding to distinct traces on the ionogram were extracted to clarify their propagation route. The new trace seen between E and F reflections on the ionogram was shown to be a reflection off the base of the cloud which was situated between the two layers in altitude (at 182 km), this new layer will be referred to as the ‘cloud layer’. The second and third new layers, known as the ‘ghost layers’ were observed to sit just above the F layer reflection, due to their geometry they are fairly indistinguishable in propagation distance or delay time. Their existence can be explained by a ray path which has deflected from the cloud to the F layer and then down to the receiver and vice versa (Figure 4). This small deviation was shown to have added enough delay to represent it as a distinct layer on the ionogram. The delay times of these two new layers were found to be strongly dependent on the position, shape and density of the cloud.

The traces found in the synthesized ionogram directly correspond to observed traces on the experimental ionogram. Furthermore, these layers have been reproduced without any input firing angle or parametrization of the ray traces; this indicates that the AFRL cloud model successfully reproduces experimental conditions, while the synthetic ionogram routines aptly capture the observed effects on HF propagation.

### 3.1 TIME EVOLUTION

The time evolution of the cloud and its corresponding effect on radio propagation was also investigated. In particular, we focused on the effect of drop in electron density with time, and how it impacts the Maximum Useable Frequency (MUF) of the newly formed layers.



**Figure 5:** The synthesized ionogram of the Rongelap to Kwajalein path is presented for a) 07:30 UT and b) 07:35 UT on the 9th May 2013. The layers due to the presence of the cloud are shown in green and blue. The red dotted line shows the theoretical maximum reflection frequency which has exponentially decayed with the cloud density.

The MUFs on all of the paths that interact with the cloud were observed to decrease in frequency with the cloud’s peak electron density. This drop in maximum frequency of ghost and cloud traces was observed in experimental ionograms and thus has been successfully reproduced by the simulated ionogram given in Figure 5, although the simulation underestimated the MUF values.

## 4. DISCUSSION & CONCLUSIONS

In all samples the synthetic ionograms reproduce the correct delay times for the respective layers seen in the experimental plots. More importantly the synthetic ionogram also contain the new layers due to an interaction with the plasma cloud. Furthermore, we hypothesise that the new layer formed between the E and F reflections is due to a reflection from the bottom of the cloud. The ‘Ghost’ layer sitting above the F layer is due to a ray scattering off the cloud to the F layer and then reflected down to the receiver. This longer route causes a small time delay as seen on both the recorded and synthesized ionograms.

There are two main limitations of the synthetic ionogram. Firstly, it doesn’t reproduce intensity variation as it uses single ray propagation. Secondly, it seems to underestimate the upper bound of the maximum frequency supported by the cloud.

It is difficult to address the intensity issue as the ionogram uses a single ray to understand propagation. A progression would be to estimate an intensity value using multiple rays. However this would be a very computationally expensive method and require an in depth study of radio propagation through the ionosphere.

The issue of finding the correct maximum frequency for a given layer is a difficult one. The intent of this software was to produce a robust transferable routine that can produce an ionogram between two ground stations in any geometry. As a consequence we have sacrificed some detail in the MUF. A resolution to this problem would be to run the code at a higher sample rate. Future work could also include a search for high angle rays which could be used to extrapolate the cut-off frequency.

## ACKNOWLEDGEMENTS

This work has been funded by the United Kingdom Ministry of Defence Science and Technology program. We would like to thank the US DoD Space Test Program (STP) and the NASA Sounding Rocket Program for their support of the MOSC Experiment. Additional support to AFRL for the MOSC Experiment was provided through the Air Force Office of Scientific Research (AFOSR).

## REFERENCES

- Caton, R.G. et al. (2013). The AFRL Metal Oxide Space Cloud Experiment (MOSC) Artificial Modification of the RF Propagation Environment. AGU Fall Meeting, SA21A-2011
- Chapman, S., (1931). The Absorption and dissociative or ionizing effect of monochromatic radiation in an atmosphere on a rotating Earth. Proc. Phys. Soc. Lond., 43, p31
- Groves, K.M, et al., (2013). The Metal Oxide Space Clouds (MOSC) Experiment: High Frequency (HF) Signatures and Interactions with the Ambient Ionosphere, AGU Fall Meeting, 2013, SA23B-05
- Jackson-Booth, N. K., Cannon, P. S., Bradley, M. and Arthur, P. A. (2012). New Oblique Sounders for Ionospheric Research. Ionospheric Radio Systems and Techniques (IRST 2012), pp1-3
- Jackson-Booth, N. K. et al. (2014). Preliminary HF results from the Metal Oxide Space Cloud (MOSC) experiment. General Assembly and Scientific Symposium (URSI GASS), 2014 XXXIth URSI, 1-4, IEEE
- Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery (1992), Numerical Recipes, 2<sup>nd</sup> ed., Cambridge University Press.