Installation of Passive Radar Corner Reflectors at the SENSE study site; Hatfield Moors, Doncaster.

Decarbonisation and Resource Management Programme

Open Report OR/21/002

BRITISH GEOLOGICAL SURVEY

DECARBONISATION AND RESOURCE MANAGEMENT PROGRAMME

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L Bateson, A Novellino, E Hussain.

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Summary

This report describes the installation of Radar Corner Reflectors (CRs) at the SENSE study site on Hatfield Moors near Doncaster, Yorkshire, England. It describes the need for the CRs on the study site, the specification, painting and modifications required for this site. It then describes the installation procedure and presents preliminary results in the satellite radar data.

1 Introduction

In the ACT funded SENSE project (https://sense-act.eu/) BGS is using the Hatfield Moor gas storage facility as an analogy for an active, onshore CO2 Capture and Storage (CCS) site. The intention is to investigate the use of satellite Interferometric Synthetic Aperture Radar (InSAR) to characterise the volume and location of injected / removed gas via changes in the surface elevation. Although gas is stored at Hatfield Moors at a lesser depth than is typical for CO2 storage, the site is being used as an analogy for the impacts of fluid injection on a porous reservoir in order to enable the SENSE project to improve understanding of the link between surface movement and CO_2 injection (CO_2 is usually stored at depths below 800 m such that the CO_2 is in its highly dense phase, thereby improving storage efficiency)

Figure 1: Location of Hatfield Moors study site, Scottish power gas injection site circled in blue. Contains Ordnance Data © Crown Copyright and database rights [2021] . Ordnance Survey Licence no. 100021290

1.1 STUDY SITE GEOLOGICAL SETTING AND CHARACTERISTICS

Hatfield Moors is a ~29km^2 peatland located in South Yorkshire to the east of Doncaster (Figure 1). It is currently part of the Humberhead Peatlands National Nature Reserve managed by Natural England (https://www.humberheadpeatlands.org.uk/). The Moors represent a remnant of a larger wetland which was known as the Humberhead levels, although now much smaller in size they are still the largest area of raised peat bog in the United Kingdom (Mitchell et al., 2020).

Peat was worked from Hatfield Moors from the thirteenth century through to 2001 (with stockpiles used until 2005), although the most was extracted during the 1980's by a technique known as peat milling. Since 2005 efforts have been in place to return the area to a condition under which peat can be formed.

The outcropping bedrock geology of the Hatfield Moors site is the Triassic sandstone of the Chester Formation (Figure 2). However this is overlain by superficial deposits consisting predominantly of Peat, with river terrace sands and gravels to the east, an ‘island’ of Glaciofluvial clays, sands and gravels and Alluvium to the west (Figure 2).

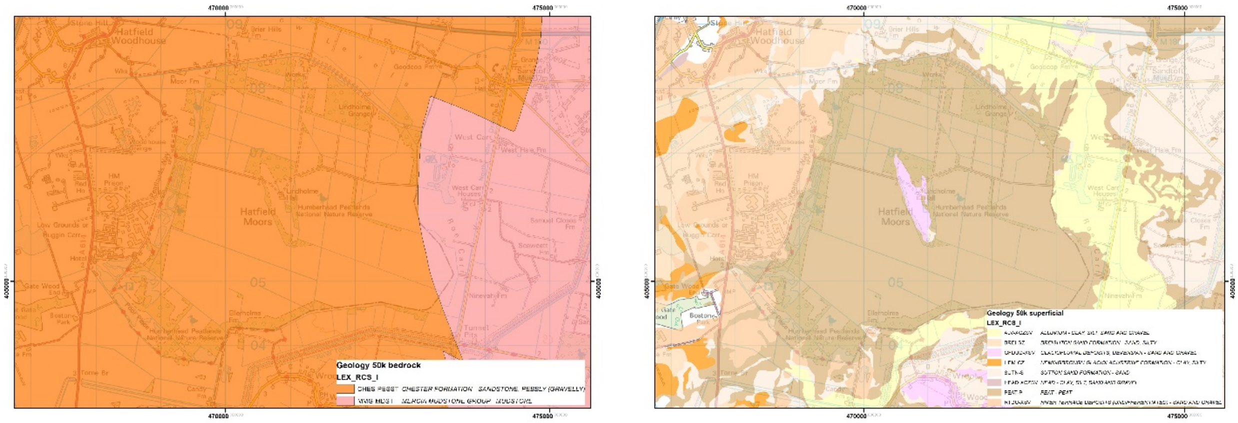

Figure 2: Bedrock geology map for the study area (left). Superficial geology map for the study area (right). Contains British Geological Survey materials ©UKRI 2021. Contains Ordnance Data © Crown Copyright and database rights [2021] . Ordnance Survey Licence no. 100021290

According to the CORINE land cover map (CORINE 2018; Figure 3), landcover within Hatfield Moors is dominated by peat bogs (~55%), non-irrigated arable land (~17%), water bodies (6%) and inland marshes (4%). Such types of terrains commonly undergo seasonal variations related to decomposition processes and weather conditions.

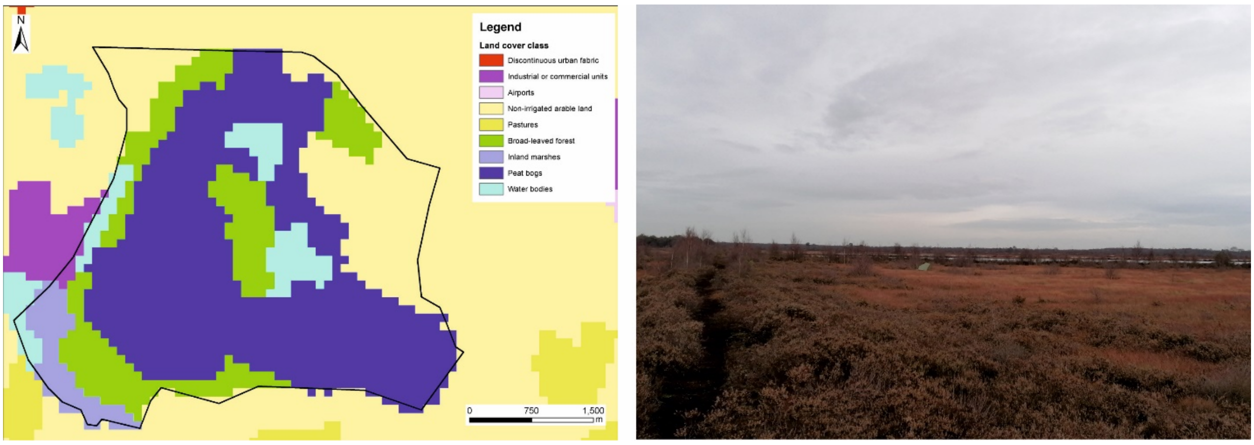

Figure 3: Land cover map for Hatfield Moors with the peatlands edge shown with a solid black line (left). Appearance of the peat bogs on site (right).

1.2 GAS STORAGE

The Hatfield Moor gas storage facility utilises a depleted gas field at a depth of approximately 440 metres to store natural gas enabling Scottish Power to manage demand and store gas for peak periods (Scottish Power, 2014). Gas is stored in the porous Oaks Rock Sandstone and sealed by a marine bed (Figure 4). The reservoir has a capacity of 116 million cubic metres and has been operational since 2000 (Scottish Power, 2014).

Gas is injected via three well heads, all are located within the Scottish Gas compound to the west of Lindhome Hall (see Figure 1). Gas is stored within the reservoir as outlined in Figure 4.

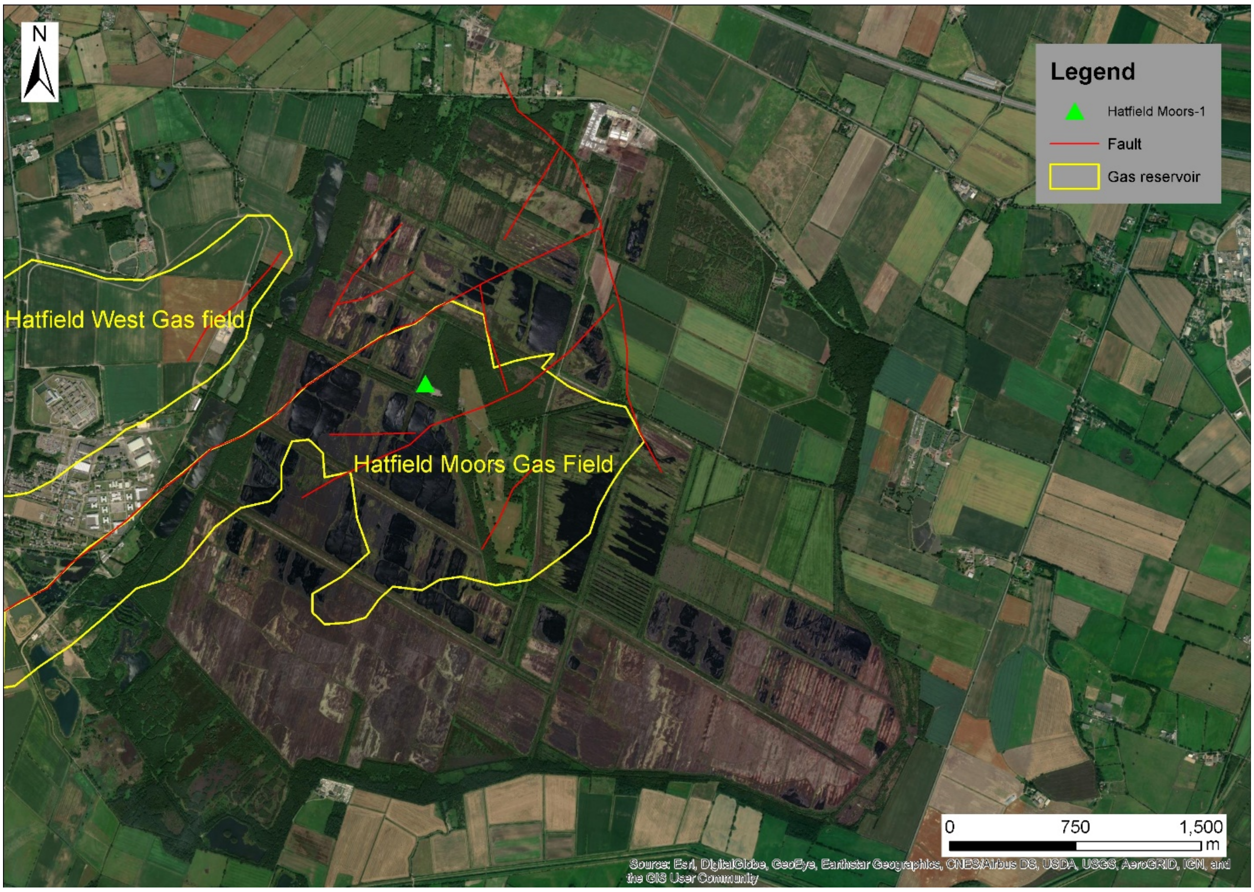

Figure 4: Location of gas storage reservoir, faults and injection well under Hatfield moors. Source of the background image: Esri - World Imagery basemap.

2 Radar Interferometry and CCS

Interferometric Synthetic Aperture Radar (InSAR) is a well-established technique for mapping surface displacements from space (Biggs and Wright, 2020) and represents a unique technology that has been widely used due to its advantage of large spatial coverage and millimetric accuracy (Minh et al., 2020).We wish to test the applicability of InSAR to onshore CCS in temperate environments such as the UK. Previous studies (e.g., Vasco et al., 2010) have shown InSAR's applicability to CCS, gas storage in other environments, most notably in deserts where the landcover is suitable for the application of InSAR.

InSAR is able to track the injection and migration of CO_2 and other gasses into the subsurface via the surface expression of the pressure changes it induces. It is therefore the intention to track the storage of natural gas, and extraction, in Hatfield Moors via its surface expression as seen by InSAR.

However, in Hatfield Moors we have the complication that it is covered by a peat bog, we therefore expect the following issue when applying InSAR here:

- The overlap of ground motions resulting from two processes; changes in volume of the gas in the storage reservoir and changes in water content of the overlying peat. In order to separate these two signals, we require high quality measurement points on the peat both on top of the storage reservoir and in areas where the gas is not stored. Differences between ground motions at these high-quality measurement points will enable us to separate the signals.

- Additionally, peat bogs and arable land are two landcover classes whose temporal decorrelation in the radar signal prevent the use of InSAR. These landcover classes typically do not allow the derivation of a measurement point and if they do the measurements have low accuracy (Cigna and Sowter, 2017).

2.1 THE NEED FOR CORNER REFLECTORS

InSAR techniques determine the motion history for pixels that, ideally, have a strong back-scatterering of the radar signal (Garthwaite, 2017) and a high temporal phase stability (Spaans and Hooper, 2016).

To measure how strong the intensity (or Amplitude^2) of the radar backscattered signal is we use a parameter called Sigma Nought (σ^0) while the temporal phase stability needed for InSAR is measured by a parameter called temporal coherence (γ).

The Radar Cross Section (RCS) is a conventional measure of the strength of radar signals reflected by a distributed scatterer. The conventional measure of brightness of a distributed target within a SAR image, the backscattering coefficient σ^0, is equivalent to the RCS (in m^2) normalised by the area A of the illuminated resolution cell (Freeman, 1992):

$$\sigma^0 = \frac{RCS}{A} \tag{1}$$

In the case of Sentinel-1, A is ~100m^2. Sigma Nought is a normalised dimensionless number, comparing the strength observed to that expected from an area of one square meter. Sigma nought is defined with respect to the nominally horizontal plane, and in general has a significant variation with incidence angle, wavelength, and polarisation, as well as with properties of the scattering surface itself (Novellino et al., 2020). The backscattering coefficient is usually expressed in decibels:

$$\sigma^0_{(dB)} = 10 \times log_{10}\, \sigma^0 \tag{2}$$

The distribution of scatterers with high σ^0 can be quite dense in urban areas (e.g., several hundred/km^2), where there are many man-made angular structures and corners to reflect incident radar energy back to the observing SAR sensor. However, in non-urban areas the distribution of strong radar scatterers may be much sparser, or even non-existent.

Coherence between two complex signals s_1 and s_2 acquired at different times and defined as their correlation coefficient (γ):

$$\gamma = \frac{E\{s_1 \times s_2^*\}}{\sqrt{E\{|s_1|^2\} \times E\{|s_2|^2\}}} \tag{3}$$

Temporal coherence is the term used for the measure of how similar an area/point is from one image to the next and is therefore a measure of how much an area has changed in terms of a radar backscatter. If an area changes a lot then the coherence is low, an example of this might be an area of trees, where the leaves are not in the same position on two images. If the area remains the same, from a radar backscatter point of view, then it has high temporal coherence.

Thresholds are set for the coherence when areas are identified as candidates for the derivation of a phase difference time series and hence an InSAR ground motion time series (Navneet et al., 2017). In simplistic terms: the higher the coherence threshold the better quality the deformation estimate. A good example of areas with high coherence are urban areas where the back scattering characteristics of a building do not change form one image to the next.

Therefore, three artificial targets have been deployed in the field to introduce point targets with high σ^0 and γ in Hatfield Moors where naturally occurring InSAR targets are sparse or non-existent given the presence of vegetation and water bodies.

Prior to CR installation SBAS InSAR processing was undertaken to understand the coherence of the study site (Figure 5). As expected the flooded areas of the moor exhibit very low coherence and areas with tree cover, taller bushes and heather show poor coherence. We were surprised that some of the areas to the SW and SE of the moor appear to have a reasonably high coherence. This is probably due to the dominance of short grasses and bare peat in these areas which do not change through time, it is encouraging and we hope to use these areas as part of the ground motion monitoring in conjunction with the CRs.

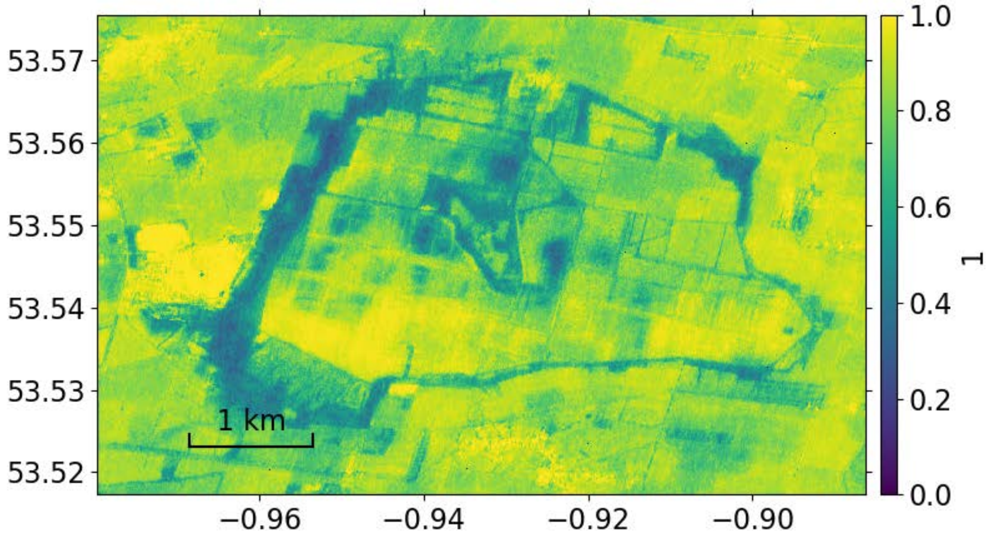

Figure 5: Temporal coherence of Hatfield moor prior to the installation of the CRs. Darker colours indicate lower coherence.

2.1.1 Passive radar corner reflectors

In this case passive Radar Corner Reflectors (CRs) are three mutually perpendicular, intersecting flat aluminium surfaces, which form a corner. This corner reflects the radar waves received from the satellite directly back towards the satellite.

The CRs have been designed by BGS (Figure 6) and manufactured by a local metal supplier. They consist of 3mm thick aluminium sheets which measure 1 m in size and are arranged in a trihedron (Figure 7).

The bottom sheet of the trihedron is bolted to a 0.9m wide by 0.5 m high hinged base; the hinge allows the elevation of the CR to be adjusted for different satellite viewing geometries and the size guarantees the mobility whilst maintaining the stability of the reflector.

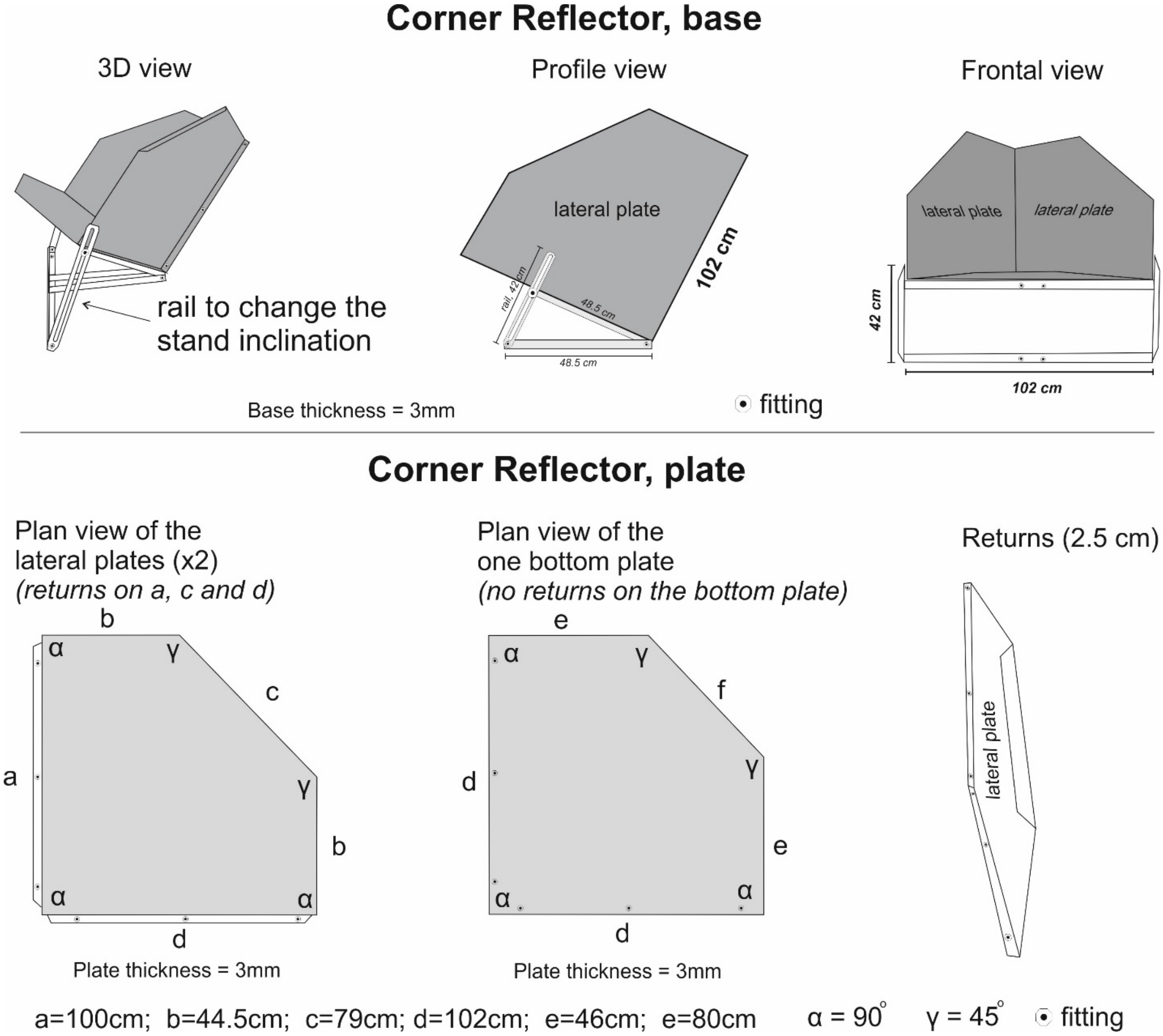

Figure 6: Technical drawings used for the production of the CR shown in Figure 7.

Figure 7: The passive Corner reflectors

2.1.2 Changes made to Corner Reflectors for Hatfield site

2.1.2.1 Painting

Since the CRs were to be installed in a National Nature Reserve operated by Natural England we were asked to paint the bare aluminium a colour that would blend in. The CRs were therefore painted a (Claas) dark green colour.

Painting aluminium first requires the use of a primer, in this case we used Hammerite special metals primer[1] followed, after an overnight drying period, by a direct to metal paint [2]. Paint was applied using brushes and rollers (Figure 8).

One side of the sheet aluminium used to construct the CRs was coated with sticky backed plastic, this was removed prior to the primer. One mistake we made was not to degrease the side of the aluminium which had not been covered by plastic. In some instances this caused the primer not to adhere to the metal as well as it should resulting in the top coat ‘blistering’ when applied.

[1] The primer is available at https://www.hammerite.co.uk/product/special-metals-primer/
[2] The paint used was https://www.paints4trade.com/direct-to-metal-paint-259051-p.asp?_=&variantid=259053&gclid=Cj0KCQiA-rj9BRCAARIsANB_4ACacggACZc5R_Z-e4AIXfianC9y4sQ14JxuGqvRnhwtGkZ0-y2lXq4aAlAjEALw_wcB

Figure 8: painting the CRs: after the primer (top) and after the final paint (bottom).

2.1.2.2 Anchoring to the peat.

We required the CRs to be well fixed to the ground so that they were not moved by the wind or animals. However, since we needed the CRs to represent the movement of the peat we did not want too deep a foundation, which would effectively anchor them to the bedrock, the CRs therefore needed to be fixed to the peat.

A 500mm long ‘hurricane ground anchor’ screw was chosen, these are metal screws with a hoop at the top. Two anchors were used per CR, one at the front and one at the back. The CR was fixed to the hoop via a U-shaped bolt, this required a total of four new holes to be drilled into the fixing points (see Figure 13).

Figure 9: Spyrabase hurricane ground anchor used to fix the CR to the peat.

2.1.3 CR Installation Location

Three locations were identified for the installation of CRs on Hatfield Moors as shown in Figure 10. These were chosen in conjunction with Natural England on a site visit during October 2020. The reasons for each location are given in Table 1.

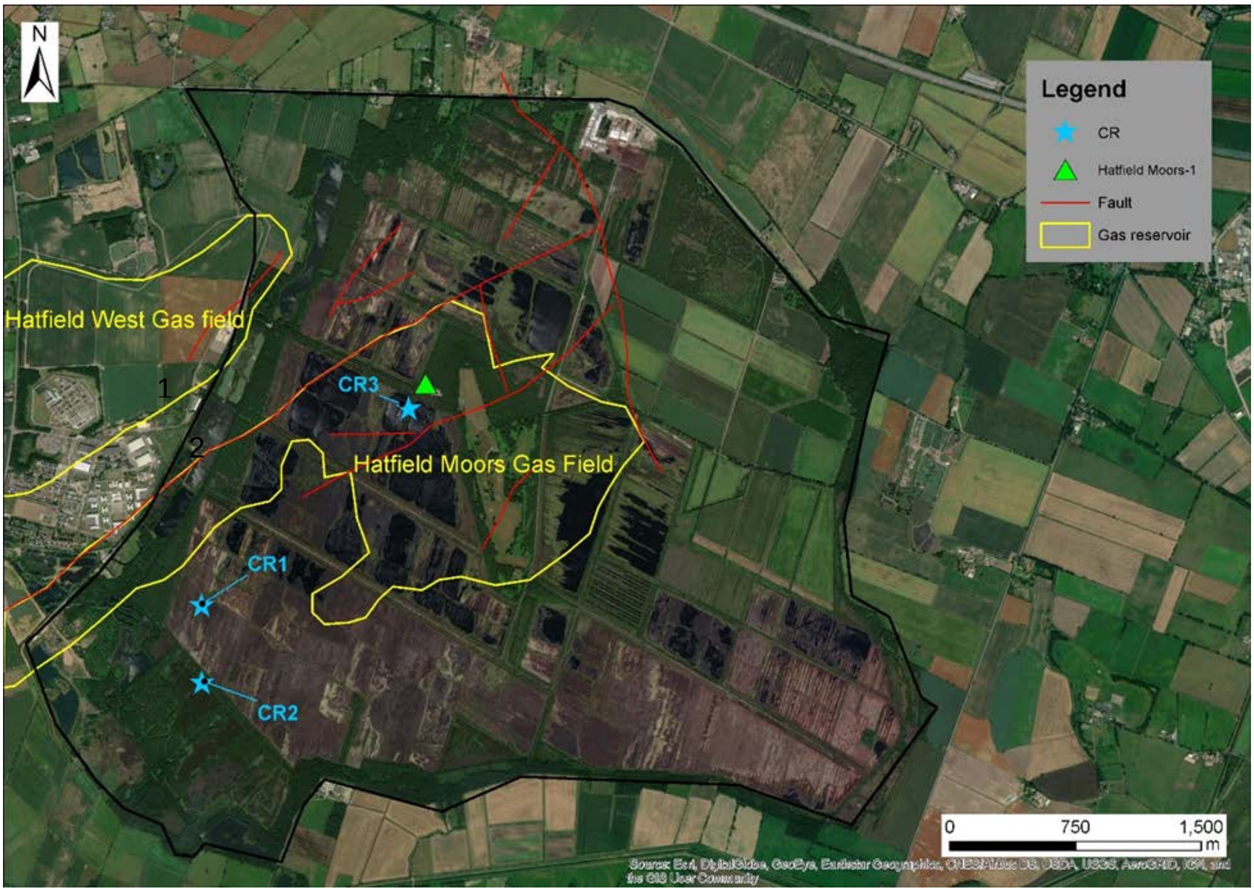

Figure 10: Location of the installation of CRs on Hatfield Moors. Source of the background image: Esri - World Imagery basemap.

Table 1: Criteria for CR locations

CR ID	Coordinates (WGS84)	Description	Reasons for chosen location
1	53.53881, -0.95675	Behind the crashed WW2 Polish bomber	• Typical area of non-flooded peat • Short grass vegetation and small (~1-1.5 m)beech/birch trees • Out of the way/not in view
2	53.53474, -0.95568	Within dense heather vegetation next to a dip well.	• On peat • Heather vegetation cover • Next to a water level monitoring dip well
3	53.55087, -0.94104	On 'headland' between two ponds on top of the peat.	• Above the gas storage reservoir and on peat • Close to the well heads • Heather vegetation

2.1.4 Installation procedure

The CR's are fairly large and heavy (~10 kg each) and were therefore transported to the installation locations form the vehicle using a cart (Figure 11). The bases had been pre-assembled at BGS but the sides were assembled on site, once assembled the sides form a 1m cube which is difficult to transport.

Figure 11: Transporting the CRs to their installation positions. Note pre-assembled base and disassembled sides

Once on site it was discovered that each reflector had two holes which had not been prepared during fabrication. These were the holes allowing the top cube to be fixed to the base. It was therefore necessary to drill these in the field. Unfortunately we did not have a battery operated drill with us (although we did have an impact driver), we therefore had to 'drill' the holes using a can opener on a Leatherman multi-tool (fortunately the aluminium is soft). Next time we recommend assembling each CR in the workshop prior to departure to ensure it all fits together and then dis-assembling for transport. We also recommend to bring a battery drill and drill bits suitable for metal.

2.1.4.1 THE STEPS FOR INSTALLATION WERE AS FOLLOWS:

1. Offer the base up the ground in the correct location and ensure it is flat and free from vegetation
2. Orient the base so that it strikes 350ºN-170ºS degrees (note we were installing for Sentinel 1 ascending geometry). We used the compass tool of a smartphone for the orientation (Figure 12).

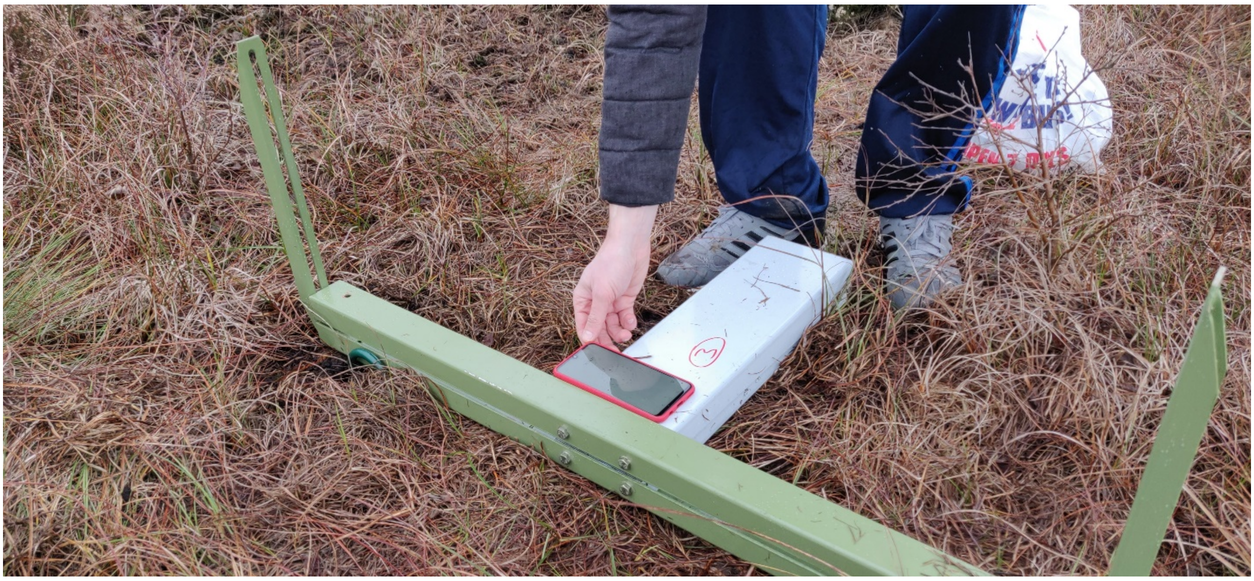

Figure 12: ensuring the base is orientated with a strike of 350ºN-170ºS to match the Sentinel 1 Ascending geometry.

3. Mark positions for ground anchors, remove base and screw in ground anchors
4. Re-position the base and fix to the ground anchor loops using the U-shaped bolts (Figure 13).

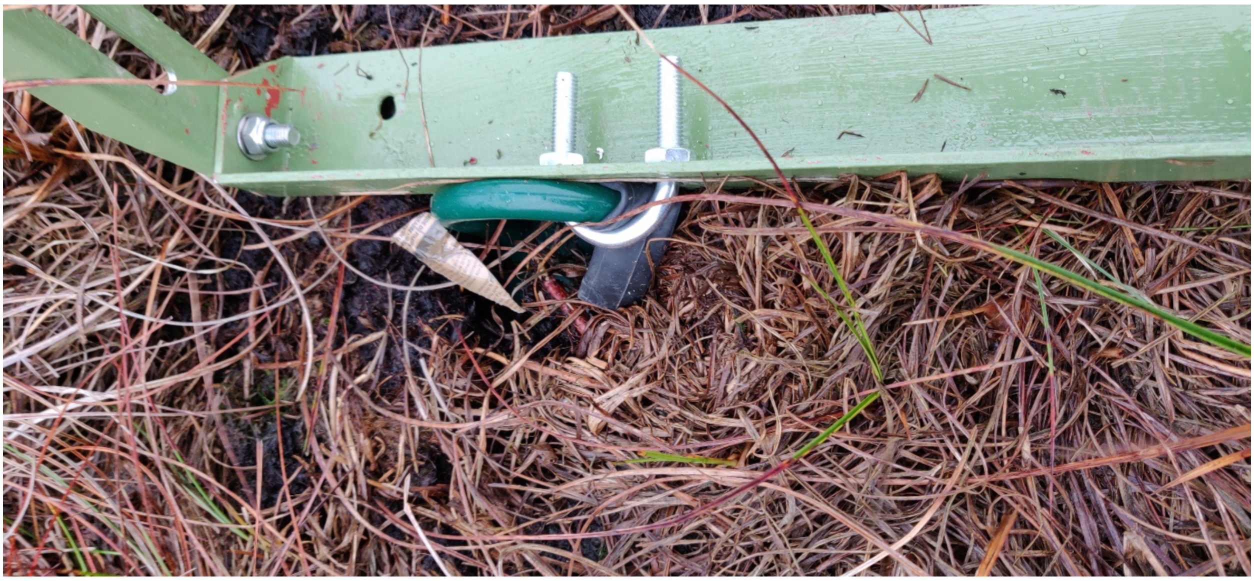

Figure 13: Fixing the CR base to the ground anchors; Top fixing at the front of the CR, bottom; fixing at the back of the CR. Note rubber inner tube offcuts to aid grip between the metal parts.

5. Adjust the elevation of the base so the CR will sit at 25º from the horizontal (Figure 14).

Figure 14: Adjust elevation to 25º.

6. Fix the three sides of the corner together and bolt to the base (Figure 15-Figure 17).

Figure 15: Installed passive Corner Reflector at location 1.

Figure 16: Installed passive Corner Reflector at location 2.

Figure 17: Installed passive Corner Reflector at location 3.

3 Preliminary Results

In the absence of sufficient time to carry out InSAR processing, which requires a sufficient number of radar images, the change in σ^0 is a preliminary check to verify the effect of the installation of the CRs.

This check has been conducted using Google Earth Engine and considers Sentinel-1 ascending data with VV polarisation.

The analysis of the 1,448 (historical) Sentinel-1 images, between 1st of January 2015 and 16th of December 2020, reveals that spatially σ^0 value over Hatfield Moors ranges between -10dB and -20dB with lower values over the peat bogs area which are usually flooded during the year (Figure 18a). If orientated correctly, the CRs should increase the reflection of the incident radar waves straight back to the radar sensor, they should therefore display a bright response when the radar amplitude image is studied. Indeed, the 22 images post installation, between 17th of December 2020 and 18th of January 2021, highlight the increase of σ^0 over the three CRs locations.

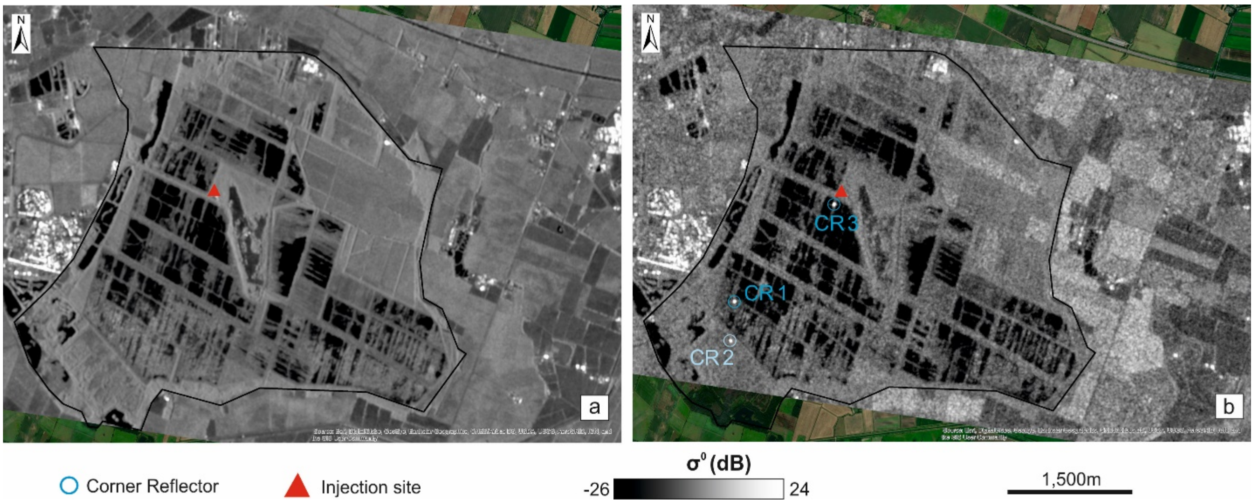

Figure 18: Sigma nought value for Sentinel-1 ascending dataset over Hatfield Moors during 1st of January 2015 and 16th of December 2020 (a) and 17th of December 2020 and 18th of January 2021 (b).

Temporally, the increase of the radar signal for the three CRs location until the 29th of January 2021 is ~18 dB higher at CR1 (Figure 19a), ~23dB higher at CR2 (Figure 19b) and ~16dB higher at CR3 (Figure 19c).

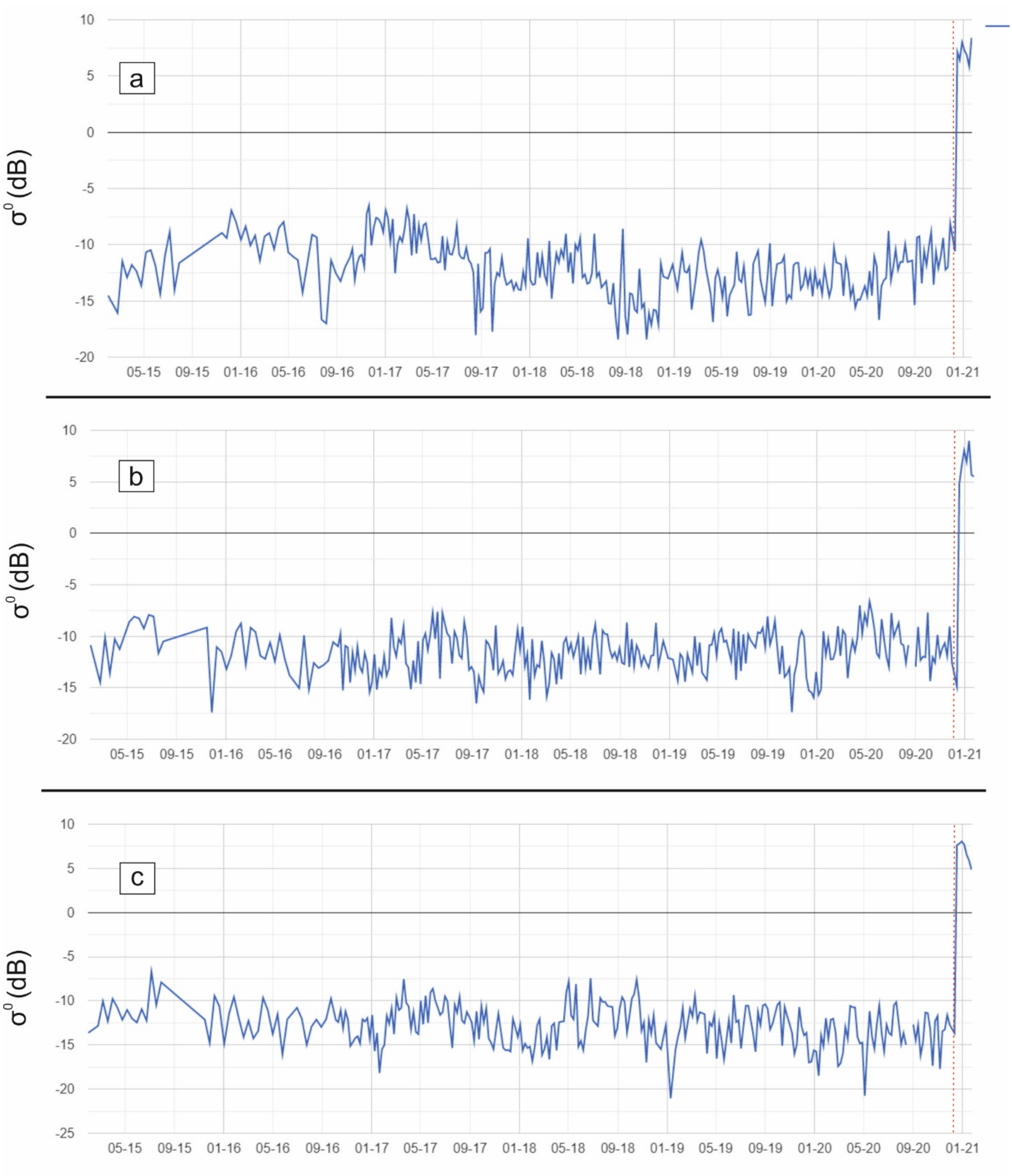

Figure 19: Time series of σ^0 at location CR1 (a), CR2 (b) and CR3 (c). Time format is in mm-yy, the red dotted line indicates the installation date for the CRs.

4 Discussions and Conclusion

We have planned for, modified and successfully installed three passive corner reflectors at the SENSE Hatfield Moors site. Preliminary analysis of the radar response to the CRs shows that they are installed in the correct orientation and have increased the sigma nought by approximately 30db. This should provide three precise targets for InSAR analysis.

InSAR processing will take place probably in April 2021 once a sufficient stack of ~20/30 Sentinel 1 images has been acquired for the area over the same ascending track (relative orbit number #132) and when gas has been withdrawn from the storage site to meet the winter heating demand.

The derived ground motions for CRs 1 and 2 are expected to be mainly composed of motions due to water level changes within the peat, whilst motions at CR 3, which sits on the gas reservoir, should contain combined motions due to the peat and the gas changes in the reservoir. It is hoped that by examining the differences between the motions at the CRs we will be able to separate the peat related motions from those in the reservoir.

Using this knowledge, gained at these highly reliable points, combined with a detailed geological understanding of the reservoir from modelling work (SENSE taskxx) we can use the lower quality, yet still numerous, InSAR measurement points across the Hatfield Moors to study the effect of gas injection into a sandstone reservoir.

Over the last two years BGS has already installed six CRs at Hollin Hill for landslide observation, two at Herstmonceux to tie in with other geodetic equipment and one CR at Keyworth to test the relationship between σ_0 and the orientation of the reflector. These have already been inserted by the Committee on Earth Observation Satellites (CEOS) on the Mission Point and Distributed Targets Database available at http://calvalportal.ceos.org/point-distributed-targets-db.

BGS is in the process of installing CRs in several other UK sites; the ERA GeoEnergy Testbed to monitor CO_2 injection and both the Glasgow and Cheshire UKGEOS sites to establish pre-subsurface research baselines. The experience gained during the SENSE work will be applied and built upon in the above projects.

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