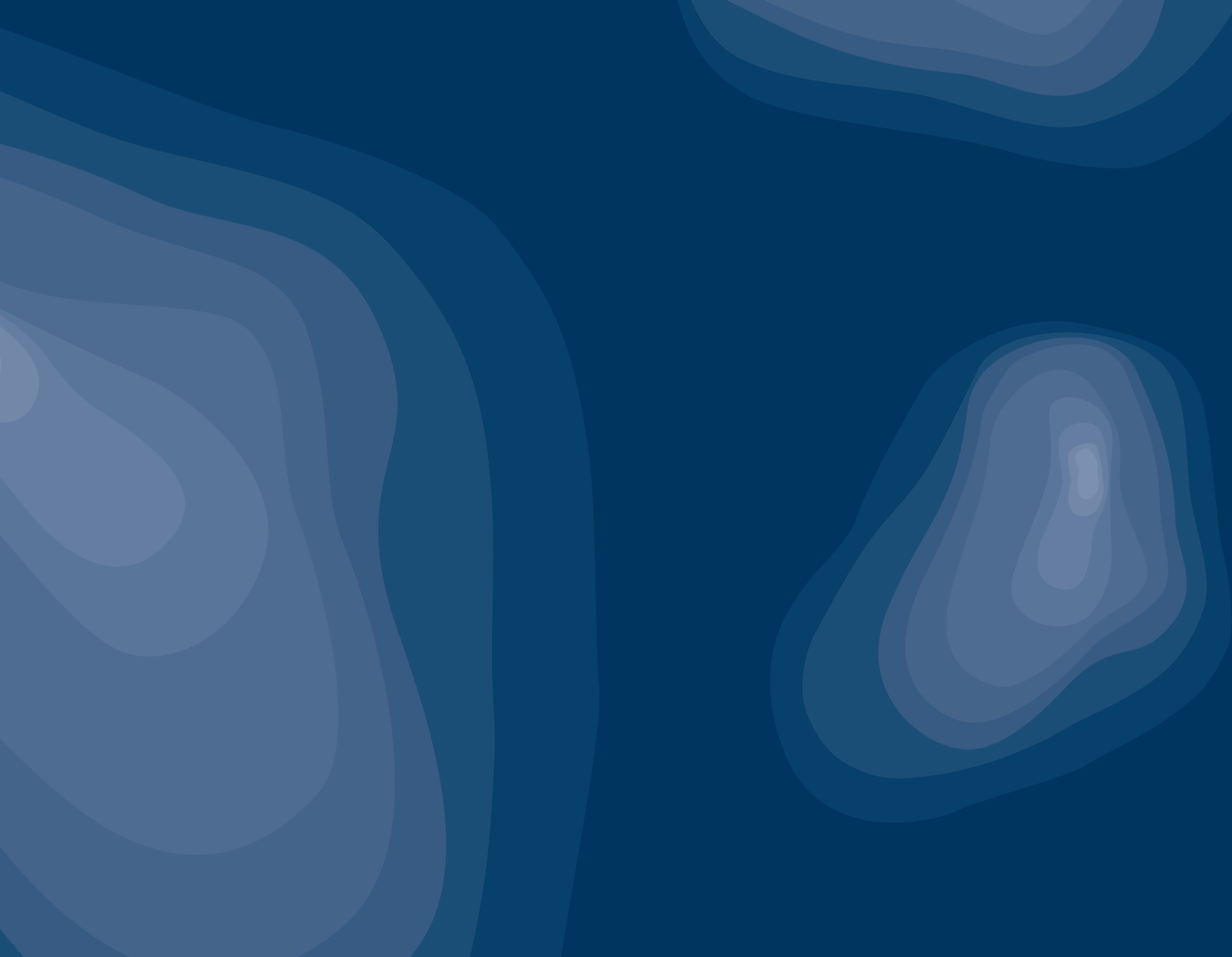
FFI-RAPPORT

19/00635

High latitude optical satellite communications

– cloud coverage in Norway

Lars Erling Bråten
Martin Rytir



High latitude optical satellite communications
– cloud coverage in Norway

Lars Erling Bråten
Martin Rytir

Norwegian Defence Research Establishment (FFI) 2 April 2019

Keywords
Satellitter
Optisk kommunikasjon
Skyer
Diversitet

FFI-rapport
19/00635

Prosjektnummer
1441

ISBN
P: 978-82-464-3182-6
E: 978-82-464-3183-3

Approvers

Richard B. Olsen, *Research Manager*
Trygve Sparr, *Research Director*

The document is electronically approved and therefore has no handwritten signature.

Copyright

Sammendrag

Trådløs satellittkommunikasjon har tradisjonelt benyttet modulerte radiobølger for overføring av informasjon til, fra og mellom satellitter. Optisk kommunikasjon benytter lignende prinsipper med elektromagnetiske bølger (fotoner) med mye høyere frekvens (THz). Den økte frekvensen fører til at hydrometeorer i form av skyer og tåke demper de optiske signalene kraftig.

I denne studien undersøker vi graden av skydekke i norske nordområder for å estimere tilgjengeligheten for optiske bakkestasjoner som kommuniserer med satellitter. Vi har benyttet tolv måneder med skybilder tatt fra værobservasjonssatellitter i 2014, og behandlet dem for å trekke ut prosentdelen av bilder som har skydekke mindre (eller større) enn en terskel. Resultatene presenteres i form av numeriske kart for deler av Norge nord for 62^0N inkludert Svalbard og havområdet rundt. Manuelle skyobservasjoner fra samme tidsperiode er benyttet for å validere resultatene. I tillegg har vi benyttet numeriske værmodeller fra Meteorologisk institutt (AROME MEPS og Arctic) som dekker hele det norske området i 2018.

Det ble funnet relativt store forskjeller mellom manuelle og satellittbaserte observasjoner, spesielt i tilfeller med lite skyer. Det understrekes at rutenettet for bildene (1,6/2,5 km grid, avhengig av datasett) ikke er direkte sammenlignbart med de manuelle observasjonene i form av skydekke for synlig (halvkuleformet) himmel. Satellittdataene og modelldataene er også fra to forskjellige år. De numeriske dataene ble benyttet til å estimere i hvor stor grad to bakkestasjoner forbedrer sannsynligheten for skyfri himmel.

Resultatene viser generelt mindre skydekke over land og øyer som Svalbard og Grønland sammenlignet med havområdene. Satellittbildene fra 2014 hadde maksimalt 59% skyfrie bilder. Lokasjonene for potensielle bakkestasjoner i Norge hadde maksimalt 33% skyfrie bilder. Verdier gitt av AROME-modellene for 2018 er mye lavere enn satellittdata, med størst forskjell på øylokasjoner. Maksimal skyfri andel var på 25% i Sør-Norge.

Bruk av to bakkestasjoner forbedrer tilgjengeligheten noe. Kombinasjon av to lokasjoner økte sannsynligheten for at minst en stasjon har skyfrie forhold i 39–54% av tiden. Dette er vesentlig mindre enn ønsket dersom målet er å oppnå optisk tilgang til satellitter i løpet av alle passeringer for en lav jordbane eller kontinuerlig kommunikasjon med geostasjonære satellitter.

En kombinasjon av mer enn to stasjoner, fortrinnsvis også sammen med radiokommunikasjon, er ventet å forbedre tilgjengeligheten i nordområdene. Samarbeid med optiske bakkestasjoner i andre land kan være nødvendig for å oppnå høy tilgjengelighet og derved nedlasting av observasjonsdata for alle satellittpasseringer.

Summary

Wireless satellite communications has traditionally utilized modulated radio waves to transfer information to, from and between satellites. Optical communications utilize similar principles with electromagnetic waves (photons) at significantly higher frequencies (THz). The increased frequency implies that hydrometeors in form of clouds and fog severely attenuate optical signals.

In this study we investigate the amount of cloud coverage within the Norwegian High North to be able to estimate the optical communications availability of a ground station communicating with satellites. We have utilized twelve months of cloud coverage images obtained from weather satellites in 2014, and processed these to obtain the percentage of images having cloud coverage less (or exceeding) a given threshold. The results are in forms of numerical maps for parts of Norway north of 62^0N including Svalbard and surrounding sea area. Manual cloud observation data from the same time period has been used to validate the results. In addition we have utilized numerical weather models from the Norwegian Meteorological Institute (AROME MEPS og Arctic) covering the complete Norwegian area for the year 2018.

Significant differences were observed, especially in cases with low cloud coverage. However, it should be noted that the image grid (1.6/2.5 km grid, depending on dataset) is not directly comparable with the manual observations of cloud coverage of the (hemispherical) sky. The satellite and model datasets also cover different years. The numerical cloud data was utilized to estimate to what degree diversity with two ground stations improves the probability of having clear sky.

In general, less cloud cover is observed over land, and islands such as Svalbard and Greenland have significantly lower cloud coverage compared to areas in the open sea. The satellite images from 2014 indicate a maximum of about 59% with cloud-free conditions. At the potential Norwegian ground locations selected for study, we observe less than about 33% cloud-free conditions. Values given by the AROME prediction models for 2018 are significantly lower than those from satellite images, especially at the island locations. The highest percentage of cloud free conditions is found in the southern Norway with values around 25%.

Two-station diversity has the potential of improving the availability, and a combination of two sites increases the probability of either one (or both) having cloud-free images to between 39 and 54%, depending on the dataset. This is significantly less than an objective of having optical access to satellites during all passes for low earth orbiting satellites or continuous communications with geostationary satellites.

A combination of more than two diversity stations, and preferably also utilizing radio frequency communications, is expected to improve the access to satellites in the High North. Cooperation with optical Earth stations in other countries may be required to ensure successful downloading of observation data in each pass.

Contents

Preface

The reported work has been carried out within FFI project 1441. The results are a contribution to the multinational project Military Optical Satellite Communications, which is a part of the Responsive Space Capabilities RDT&E Memorandum of Understanding.

1 Introduction

Satellite communications utilizing wavelengths in the optical part of spectrum is an interesting alternative to utilizing longer wavelengths in the radio part of the spectrum. In this report we consider optical wavelengths to be 100 μm or shorter (3 THz), and radio wavelengths to be 1 mm or longer (300 GHz). The wavelengths of main interest for optical communications to and from satellites are 1550 and 1064 nm.

Clouds are considered to be the main propagation degradation factor for optical communications [1]. FFI has previously studied the cloud cover in parts of the Arctic as part of an electro-optical payload for maritime surveillance [2]. Cloud cover images (1200 x 1200 pixels, 1600 m x 1600 m) acquired by the satellites MetOp-A, NOAA-18 and NOAA-19 were utilized. The images cover an area enclosed by the polygon given in Table 1.1, for details of the data source see [2]. In the current study we utilize the same cloud cover data, reprocessing it to obtain the main characteristics relevant for optical communications between a terrestrial optical terminal and a satellite.

Latitude (deg.)	65.6926	62.3084	82.1753	74.2854
Longitude (deg.)	-7.4845	29.9644	-24.2166	63.1304

Table 1.1 Polygon enclosing the investigated Artic area covered by satellite images.

For each pixel the cloud cover is given as a percentage of the sky covered by clouds. The dataset processed covers the time from 01-Jan-2014 to 31-Dec-2014 with 7349 images. Two example images from December 2013 are shown in Figure 1.1.

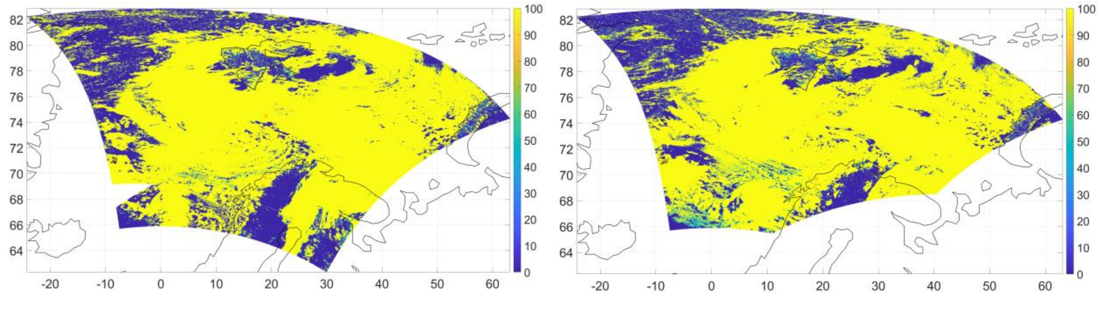
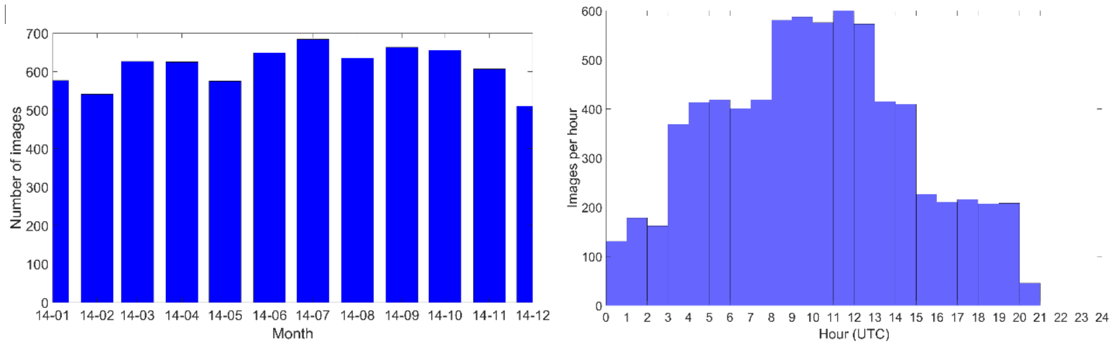


Figure 1.1 Examples of cloud cover images from the MetOp 02 satellite, December 2013.

The numerical cloud coverage values available in the current work were 0, 50 and 100%. The distribution images per month and the distribution between the hours of the day (in UTC time) are shown in Figure 1.2 a) and b), respectively.



a) *b)*

Figure 1.2 Image time distribution. a) per month, b) per hour (UTC time).

There is a relatively even distribution of images per month. The diurnal histogram shows that no images are taken after 21 in the evening. The frequency of images per hour is higher during the time period between 8 and 13. In [2] it was found that the cloud cover is close to constant throughout the day. The following cloud cover image analysis is given in terms of percentage of images. In practice this can be interpreted as close to the percentage of time. Manual cloud cover observations provided by the Norwegian Meteorological Institute (MET Norway) for selected locations have been utilized to verify the results.

For additional analysis, two different datasets from the MET Norway were utilized. The datasets come from AROME MEPS (MetCoOp Ensemble Prediction System) and AROME-Arctic which are a NWP (Numerical Weather Prediction) models covering Scandinavia and the Nordic Seas (MEPS) and areas around Svalbard (Arctic). The MEPS model is operated in cooperation between MET Norway, Swedish Meteorological and Hydrological Institute (SMHI) and Finnish Meteorological Institute (FMI).

Both AROME models have a horizontal resolution of 2.5 km, 65 vertical levels, and are executed four times daily (00, 06, 12, 18) for up to 66 hours. Lateral boundary data is from ECMWF (European Centre for Medium-Range Weather Forecasts) HRES model. The main difference is that the AROME-Arctic model uses different weighting for data from satellite observations. This is due to the fact that there is very little ground observation data available in the arctic while the coverage for earth observation satellites in Low Earth Orbit (LEO) orbit is much better than further south with higher number of passes.

For this study data from the midnight (00) predictions were utilized, starting from 6 hours after the run and extending for 24 hours until the next prediction was available. The first 6 hours of each prediction are omitted based on recommendation from MET Norway. The value utilized in this study was “cloud_area_fraction” which gives a percentage value of cloud coverage for each pixel at 3 vertical levels (for MEPS). In this study the maximum value of the three levels was used in each of the pixels. For Arctic there is only a single “cloud_area_fraction” value at each pixel. An example cloud cover prediction is given in Figure 1.3, showing the geographical coverage of both models.

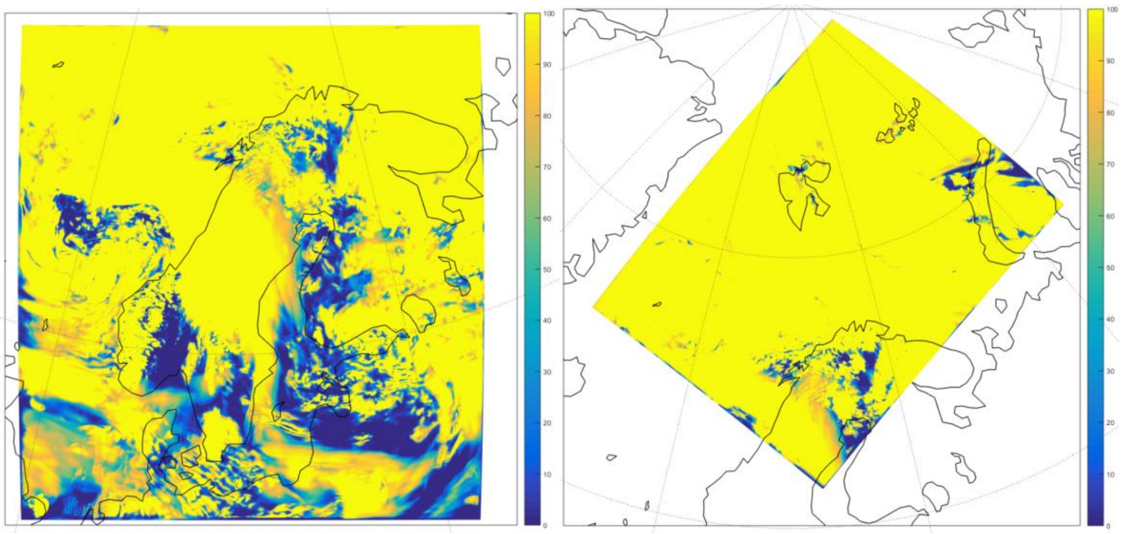


Figure 1.3 *Example AROME MEPS (left) and AROME-Arctic (right) cloud coverage prediction (%) for 06 UTC 05/08/2018 based on prediction from 00 UTC.*

The two AROME models overlap over a large area in northern Norway, some locations in this area were therefore used to compare the two prediction models and see if they can be used together in diversity studies. Timeseries comparison tests at these locations (Tromsø, Bardufoss, Vadsø) showed median difference of 2% between the two models. In areas close to the edge of model coverage the errors are larger. Combination of results from them should therefore not lead to large errors, as long as the locations are not located close to the edges of model coverage.

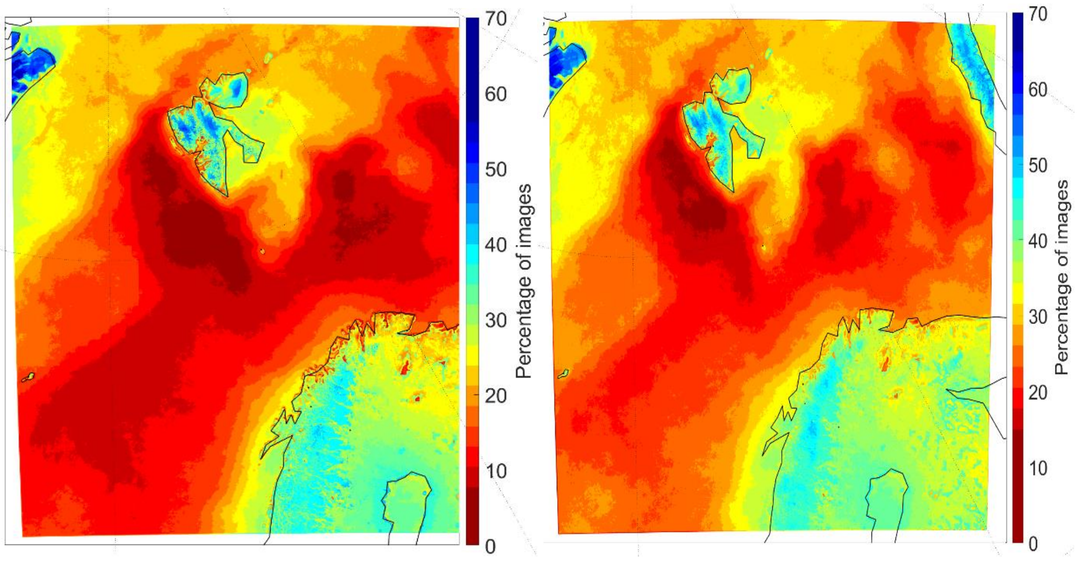
2 Cloud coverage

It is of interest to investigate where an optical ground station is expected to function satisfactory with respect to cloud coverage, and where it is not expected to function. Low cloud coverage percentages imply that optical communications in most cases would function satisfactory.

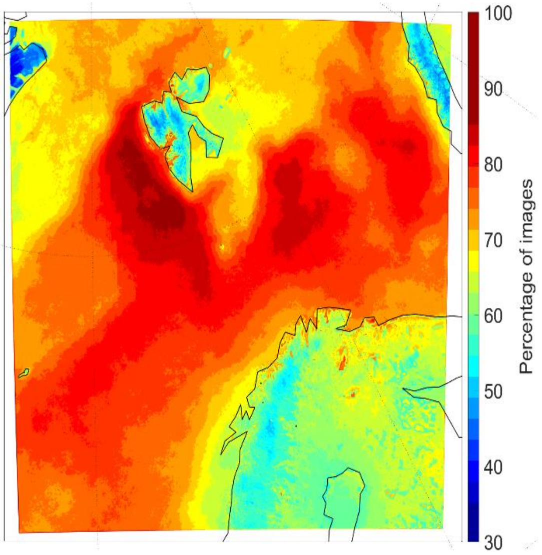
We have utilized three different types of data for cloud coverage (satellite observations, numerical weather models and ground observations for verification). The main motivation for including multiple data sources is the relative large variations for cloud coverage obtained from the different sources for the same time period. Having access to several independent datasets increase the confidence in the results. The second reason is the limited availability of data combined with significant yearly, seasonal and monthly variations in cloud coverage.

2.1 Satellite image data (2014)

The percentage of observations with cloud free conditions, cloud coverage less than or equal to 50% and completely overcast is shown in Figure 2.1 a-c.



a) *b)*



c)

Figure 2.1 Percentage of observations with clear sky (a) cloud cover is equal to or less than 50% (b) completely overcast (c).

Unfortunately, there are no mainland locations within the investigated area where the percentage of observations with cloud free conditions is close to 100%. The same also applies to ocean areas.

The maximum time percentage for cloud free conditions is 59%, found at 80.4^{0}N, 58.8^{0}E. Regions between Kiruna (Sweden) and the Norwegian border towards Narvik seem to have favorable conditions, with Kiruna airport (and Esrange) having cloud free conditions in 29% of the images.

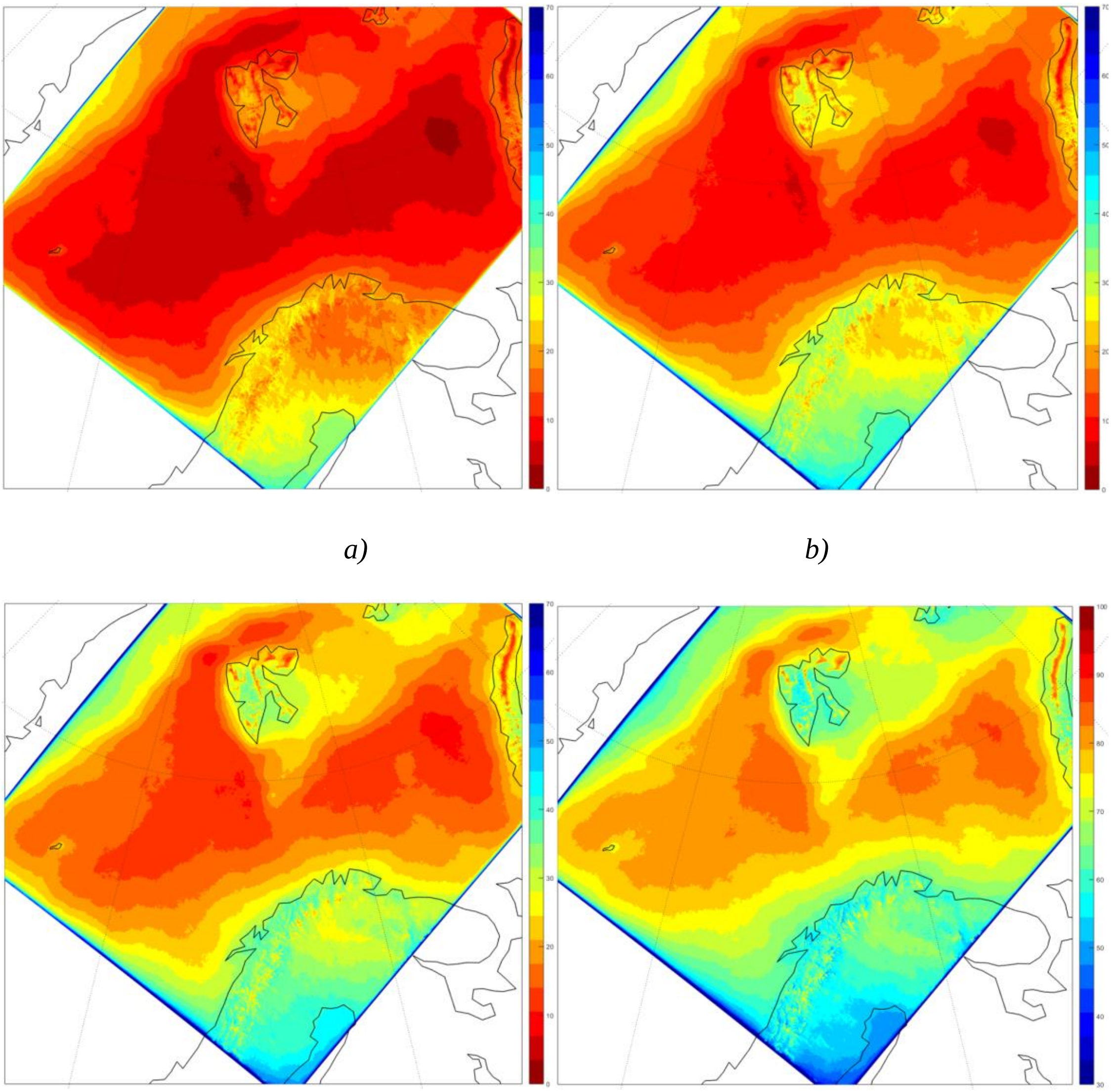
We expect significant yearly and monthly variations in the cloud coverage, and the 12 months investigated is not representing a long term average.

2.2 AROME-Arctic Predictions for 2018

For 2018 AROME-Arctic prediction data, the percentage of predictions where the cloud coverage was equal to or less than 5%, 25% and 50% is shown in Figure 2.3 a)-c) the probability of cloud cover equal to or exceeding 75% in d) .

Svalbard and the Norwegian mainland have the lowest cloud coverage values. The cloud prediction model also seems to introduce some erroneous values the edges of the grid.

The absolute values are quite a lot lower than those from satellite images in Chapter 2.1. The prediction model also gives much less variability across the map. The differences are lowest for ocean areas and for higher percentages of cloud coverage (50–75%) and largest for inland locations and low percentage of time (less than 5%). Overall both data sources agree on which areas have lower coverage relative to others.



a) b)

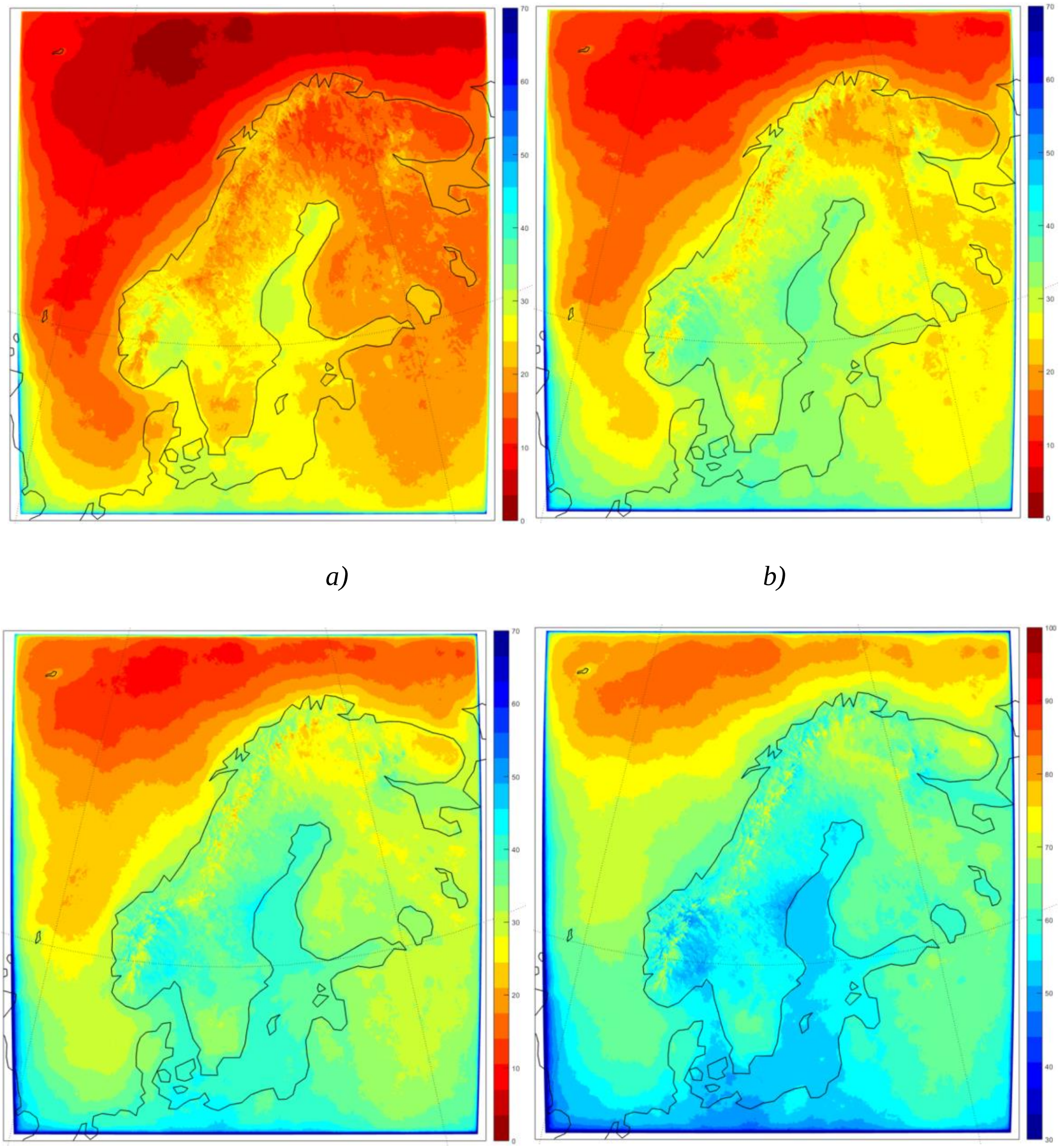
c) d)

Figure 2.2 Percentage of year cloud cover is less than 5% (a), 25% (b), 50% (c) and equal to or exceeding 75% (d).

Note that there are quite a few differences between the datasets. Most notably, the data are from different year (2014 vs 2018) and one dataset is from observation while the other is based on numerical predictions.

2.3 AROME MEPS Predictions for 2018

The AROME MEPS prediction data covers also south of Norway and it is therefore interesting to compare it with data from further north. For 2018 the percentage of predictions where the cloud coverage was equal to or less than 5%, 25% and 50% is shown in Figure 2.3 a)-c) the probability of cloud cover equal to or exceeding 75% in d) .



a) b)

c) d)

Figure 2.3 Percentage of year cloud cover is less than 5% (a), 25% (b), 50% (c) and equal to or exceeding 75% (d).

Lowest cloud coverage values are found in the south of Norway with less than 5% of the sky covered for a little more than 30% of the time. Cloud coverage in this area is also lower than that found for the northern areas by the AROME Arctic model.

2.4 Ground observations of cloud coverage (2014 and 2018)

We have used ground observed SYNOP (surface synoptic) cloud coverage observations data in an attempt to verify the results. Fractional cloud coverage (in oktas) was downloaded from https://frost.met.no/ [3] for selected locations and analyzed in Matlab. For fully overcast situations the numerical value is 8, while 0 corresponds to completely clear sky (see Figure 2.4). A value of 9 indicates that the sky is totally obscured due to for example fog or snow.

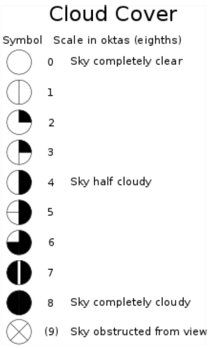
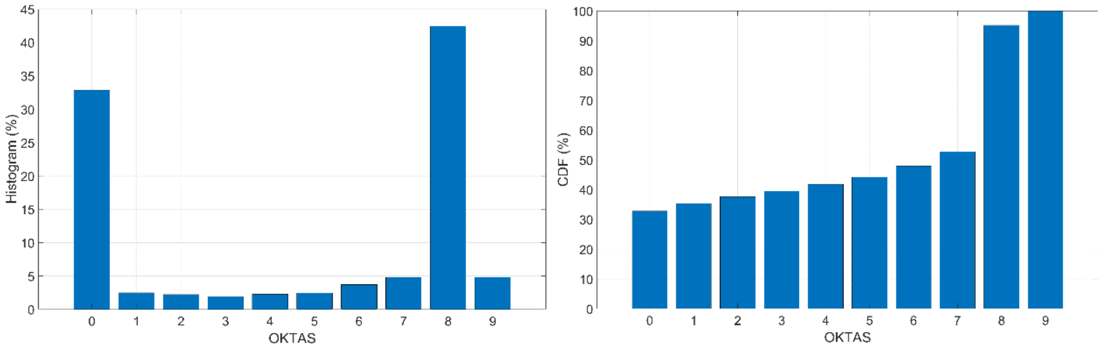


Figure 2.4 Scale of cloud cover measured in oktas (Source: https://en.wikipedia.org/wiki/Okta).

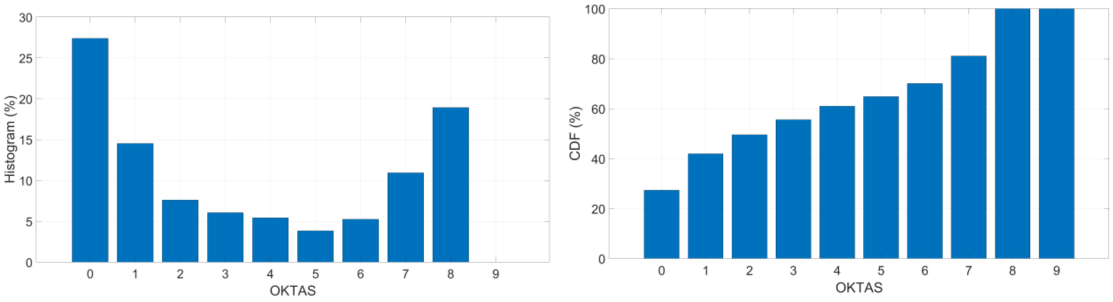
To get comparable results the same time interval (01-Jan-2014 to 31-Dec-2014) was selected as for the satellite data.



a) *b)*

Figure 2.5 Cloud observations Tromsø airport. a) Normalized histogram, b) Cumulative distribution function (CDF).

The less than or equal to half of the sky is cloudy in 42% of the observations in Figure 2.5 b. The SYNOP results for the research (and data download) station Troll in Antarctica are shown for comparison in Figure 2.6. The results for Troll are somewhat encouraging and suggest that further analysis of this location, and possibly implementation of an optical downlink station, may be useful.



a) *b)*

Figure 2.6 Cloud observations Troll, Antarctica. a) Normalized histogram, b) Cumulative distribution function (CDF).

2.5 Comparison of results (2014 and 2018)

The SYNOP data is based on manual observations of the cloud coverage in a hemisphere above the observer while the satellite data gives percentage of clouds within each of the 1.6x1.6 km pixels, and the AROME data within 2.5x2.5 km pixels. The three types of observations are thus not directly comparable, but are expected to result in similar values [1].

The SYNOP results for Tromsø airport shows that it is completely clear sky in 33% of the 8590 observations for the selected time period, see Figure 2.5 a. The corresponding value from Figure 2.1 a (clouds free) is 29%. Other example values are given in Table 2.1, including also Svalbard Platåberget (SYNOP data from the airport), Bear Island, Jan Mayen, Bardufoss, Gardermoen and Troll in Antarctica (72.0^{0}S, 2.5^{0}E). See Appendix A for a map of the locations.

The SYNOP data is based on manual observations at selected hours of the day with larger uncertainty during dark conditions, and according to [1] there seem to be an underreporting of 0 and 8 oktas. Significant deviations between ground observations and satellite data are observed for all five locations in Table 2.1 with the exception of Tromsø where there is a good agreement between satellite data and SYNOP observations.

The ground observations show a significantly lower time percentage of cloud free conditions compared to both the satellite observations and AROME data. The differences are largest for the island locations (Svalbard, Bear Island, Jan Mayen). But there are large also large differences found for some continental locations. For ≤ 50% and ≥ 75% thresholds the values are much closer to each other for all datasets. AROME data match on closely on all locations while Satellite data still shows some differences at the northernmost locations.

	2014				**2018**		
Cloud cover	0% (0 oktas)	≤ 50% (≤ 4 oktas)	≥ 75% (≥ 6 oktas)		0% (0 oktas)	≤ 50% (≤ 4 oktas)	≥ 75% (≥ 6 oktas)
Svalbard							
Satellite data	*33*	*44*		AROME Arctic	*12*	30	63
SYNOP	*0.9*	*31*	64	SYNOP	*2.5*	31	64
Bear Island (Bjørnøya)							
Satellite data	*24*	*33*		AROME Arctic	6.7	20	74
SYNOP	*0.3*	*14*	*80*	SYNOP	2.6	15	80
Jan Mayen							
				AROME MEPS	8	20	75
Satellite data	*25*	*35*		AROME Arctic	8.6	21	74
SYNOP	*0.8*	*18*	*78*	SYNOP	0.5	13	81
Tromsø							
				AROME MEPS	*16*	32	61
Satellite data	29	37		AROME Arctic	19	37	57
SYNOP	33	42	56	SYNOP	*27*	35	63
Bardufoss							
				AROME MEPS	*17*	34	60
Satellite data	*30*	40		AROME Arctic	*20*	37	56
SYNOP	*3.7*	35	59	SYNOP	*3*	31	63
Gardermoen							
				AROME MEPS	*21*	37	57
				SYNOP	*6*	39	55
Troll (2017-2018)							
				SYNOP	27	61	35

Table 2.1 Percentage of time with cloud cover, satellite data, AROME data and observations, differences of more than 10% are highlighted.

3 Spatial diversity

The results obtained in the previous section shows that no single location in the Norwegian High North likely has an annual cloud cover small enough to successfully operate as a high availability optical station.

Spatial diversity is one method to increase the availability when clouds, and perhaps more important, precipitation, is causing outages at radio frequencies [4]. In this section we investigate whether similar temporal-spatial earth station diversity is effective also in the optical domain to counteract outages due to clouds.

The previous chapter has shown that the accuracy of the data (especially for cloud-free conditions) is hard to determine. However, it should be possible to compared values for same locations within the same dataset in order to give an estimate of the performance of spatial diversity schemes.

3.1 Satellite data based spatial diversity in 2014

Downloading of polar satellite observation data is commonly performed from Svalbard, and also Tromsø is utilized. The satellite observations of cloud cover enables extraction of the probability of at least one of the two locations have cloud free conditions at the same time. This is an indication for probability of successfully downloading observation data utilizing optical communications, although the time delay between the download time instants depends on the specific satellite orbit. As seen in Table 2.1 the probability of cloud free conditions are 29 and 33% at Tromsø and Svalbard, respectively.

The estimated probability for at least one of two given locations has a simultaneous cloud cover below a given threshold denotes the two-station diversity availability probability. For this dataset we have investigated the locations Svalbard Platåberget (SVP), Bear Island (BEI), Vadsø (VAD), Tromsø Airport (TRO), Bardufoss (BAR) and Jan Mayen (JAM). We calculate the diversity probabilities as fraction of images where the cloud cover conditions are fulfilled, roughly corresponding to the% of time.

The diversity availability probabilities for cloud free conditions are given in Table 3.1. Single site probabilities are found by reading off the diagonal values. The highest two-station diversity availability for cloud free conditions (54% of satellite images) occur for the combination Svalbard and either Bardufoss or Tromsø, see Table 3.1.

The diversity probabilities for cloud cover $\leq$ 50% are presented in Table 3.2. Cloud coverage of 50% or less indicates a reasonably probability that the satellite will have a line-of-sight to the station at some time, depending on the orbit and cloud location(s).

	SVP	BEI	VAD	TRO	BAR	JAM
SVP	33	48	47	53	**53**	48
BEI		24	38	45	46	41
VAD			20	41	41	39
TRO				29	41	46
BAR					30	47
JAM						25

Table 3.1 Two-station diversity availability probability for satellite observation data, cloud free conditions.

The highest two-station diversity availability for cloud free conditions (54% of satellite images) occur for the combination Svalbard and Bardufoss, see Table 3.1. This is approximately 20% increase from single site value.

The diversity probabilities for cloud cover ≤ 50% is presented in Table 3.2. Cloud coverage of 50% or less indicates a reasonably probability that the satellite will have a line-of-sight to the station at some time, depending on the orbit and cloud location(s).

	SVP	BEI	VAD	TRO	BAR	JAM
SVP	44	62	63	64	**66**	62
BEI		33	54	55	59	54
VAD			33	54	57	55
TRO				37	51	57
BAR					40	60
JAM						35

Table 3.2 Two-station diversity availability probability for satellite observation data, cloud cover ≤ 50%.

Again it is the combination Platåberget (Svalbard) and Bardufoss that produces the best result with an availability of 66%, although several other combinations give similar values. The increase from single site value is again about 20%. Notably the combinations of Vadsø with Bardufoss and Tromsø show the same increase. This is interesting as the distance between these (~ 450 km) is only about half the distance from Tromsø to Svalbard (~ 900 km).

The obtained improvement by utilizing two-station diversity within the investigated area is rather limited, as the goal is to ensure a close to 100% downlink availability for each satellite pass. A combination of ground stations at high and middle latitudes might improve the possibility of having clear sky towards the satellite(s), although fewer polar LEO passes are visible from the southern ground station.

3.2 Spatial diversity for AROME data in 2018

For AROME data spatial diversity calculations for two station combinations were done for 9 locations in the AROME Arctic coverage area and 13 in the AROME MEPS area. There is some overlap between the areas that allows a comparison of values.

The full results for all these stations are given in Appendix A.1, here only a few stations comparable with the Satellite data are shown. For cloud free conditions given in Table 3.3 the values are lower than for the satellite data for the island locations (SVP, BEI, JAM). The differences are lower for the locations on the mainland and the improvement from single site is similar (20%). The best combination is Bardufoss in the north with Oslo in the south.

	SVP	BEI	VAD	TRO	BAR	JAM	OSL
SVP	12	18	25	29	30	20	35**
BEI		7	20	23	24	15	31**
VAD			15	29	31	23	34*
TRO				19	26	26	38*
BAR					20	27	39*
JAM						9	31*
OSL							25*

*Table 3.3 Two-station diversity availability probability for AROME data, cloud free conditions. * values from AROME MEPS, **combined MEPS and Arctic.*

For 50% or less cloud coverage in Table 3.4 the values are again higher than satellite data for island locations, but similar for mainland data. Improvement from single site is up to 30%.

	SVP	BEI	VAD	TRO	BAR	JAM	OSL
SVP	30	42	54	56	57	45	60**
BEI		20	47	47	48	37	54**
VAD			35	55	56	49	60*
TRO				37	48	51	62*
BAR					37	52	62*
JAM						21	54*
OSL							41*

*Table 3.4 Two-station diversity availability probability for AROME data, 50% or lower cloud coverage. * values from AROME MEPS, **combined MEPS and Arctic.*

Table 3.5 shows diversity calculations for different combinations of 3, 5 or 7 stations using the AROME data. Not even 7 stations are enough to achieve close to 90% probability of clear sky. Relative to best two station combinations the improvement for clear sky conditions is 7 and 16% for 3 or 5 stations in total. At 50% or lower cloud coverage level the respective improvement over the best two station combination is 11 and 20% with 3 or 5 stations in total.

	≤0.5%	≤5%	≤50%
3 stations (TRO, SVP, BAR)	35	44	64
3 stations (TRO, SVP, KIR)	38	47	68
3 stations (EGG, BAR, VAD)* –M3	44	54	73
3 stations (TRO,SVP, OSL) **	46	55	73
5 stations (TRO, SVP, VAD, BAR, KIR)	49	60	79
5 stations (KJL, ROR, BAR, TRO, VAD)* –C5	51	62	81
5 stations (EGG, BAR, VAD, ORL, FAU)* –M5	55	63	82
7 stations (EGG, BAR, VAD, ORL, FAU, LIL, POR)* –M7	62	71	87

Table 3.5 *Probability of cloud coverage lower or equal than a given threshold for multiple station combinations. *AROME MEPS data **combined AROME MEPS and Arctic data.*

4 Temporal characteristics and temporal diversity

While first order statistics of cloud coverage are important, the distribution of cloud and cloud-free periods is also important, especially for earth observation satellites with multiple passes. Figure 4.1 shows the distribution of gaps in sky visibility. “2 hours”, means that it takes 2 hours from last period of good sky visibility until the next one. In other words, that there was 1 hour period with obscured sky. This period is called gap in Figure 4.1. Note that the temporal resolution of the dataset is 1 hour. From the figure, it is clear that the majority of gaps are shorter than 4 hours, both for single site and for combination of multiple sites.

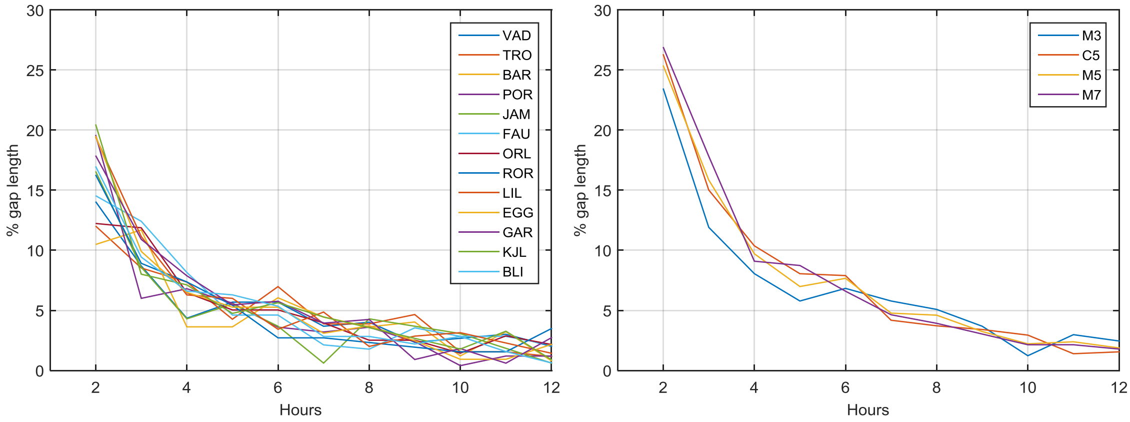


Figure 4.1 Conditional probability density function for gaps in sky visibility (cloud coverage > 0.5%) for single stations (left) and diversity combinations (right).

It is therefore interesting to have a look at the probability of cloud coverage within a certain time window so that for example earth observation satellites can download their data on a different pass. The calculation for single sites is given in Table 4.1 and for combination of multiple sites in Table 4.2.

90% probability of cloud-free sky is achieved either at 3 sites over 24 hours or at 7 sites over 12 hours. To have a 90% probability of cloud coverage equal or less than 50% of the sky 3 stations have to be utilized for 6 hours, 5 stations for 4 hours or 7 stations for 2 hours.

	Cloud coverage ≤0.5%							Cloud coverage ≤50%					
	1 h	2 h	4 h	6 h	12 h	24 h		1 h	2 h	4 h	6 h	12 h	24 h
VAD	11	15	20	25	36	52		32	39	48	55	67	81
TRO	16	19	24	29	38	52		32	38	45	51	63	78
BAR	17	20	25	29	39	52		34	40	49	55	68	83
POR	10	13	18	21	31	44		31	37	46	52	66	80
JAM	8	10	13	15	22	32		20	24	31	35	46	62
FAU	17	21	26	30	40	53		34	39	47	53	67	82
ORL	19	22	27	32	42	56		34	40	48	54	67	83
ROR	13	16	21	25	34	48		33	39	48	55	68	83
LIL	25	29	35	40	51	66		43	48	55	60	70	81
EGG	24	28	33	38	48	63		42	47	55	61	71	82
GAR	21	25	31	35	46	60		38	43	49	55	65	76
KJL	22	26	32	37	47	61		40	44	52	57	68	80
OSL	25	29	35	39	50	65		41	46	53	58	68	80

Table 4.1 Probability of cloud coverage within a given time window for single sites, 1h is the dataset resolution.

	Cloud coverage ≤0.5%							Cloud coverage ≤50%					
	1 h	2 h	4 h	6 h	12 h	24 h		1 h	2 h	4 h	6 h	12 h	24 h
3 sites – M3	44	50	59	66	79	91		73	79	86	90	95	98.8
5 sites – C5	51	58	68	75	75	94		81	86	92	94	97	99.4
5 sites – M5	55	62	71	77	87	95		82	88	93	95	98	99.8
7 sites – M7	62	68	77	82	91	97		87	91	95	96	99	99.8

Table 4.2 Probability of cloud coverage within a given time window for multiple station combinations, 1h is the dataset resolution.

5 Data access for polar orbiting satellites

The ability to download data from polar orbiting LEO satellites depends not only on the cloud coverage but also on the location and thereby potential visibility of the satellite itself. For locations further north, more satellite passes are visible so that the "access time" for optical communication system increases even if the cloud coverage is the same.

Simplified calculations of this effect are shown in Table 5.1, given cloud free conditions, for a few locations evenly distributed from north to south. For the southern locations the lower amount of cloud coverage counteracts the reduced geometric access time so that the optical access time is much larger than in northern Norway.

	Number of passes visible	Geometric access time (% of SVP)	Cloud free conditions (% of year)	Optical access time (% of SVP)
Svalbard	15	100 (12033 s/day)	12	100 (1444 s/day)
Tromsø	13	80	16.4*(19)	107 (127)
Fauske	13	76.6	17.4*(21)	108 (134)
Ørlandet	12	68.2	18.9*	108
Oslo	10	63.5	25.2*	132

*Table 5.1 Access time comparison for a sun-synchronous LEO satellite at 800 km altitude and given cloud conditions. *values from AROME MEPS, other values are from AROME Arctic.*

Since the cloud-free data showed largest errors when comparing between the three datasets (AROME, SYNOP and Satellite data) the same calculation was also done for cloud coverage of 50% or less. Surprisingly, the values given in Table 5.2 lead to a completely opposite conclusion. The much higher geometric access time on Svalbard ensures also higher optical access time even though the cloud coverage is higher.

	Number of passes visible	Geometric access time (% of SVP)	Cloud coverage of 50% or less (% of year)	Optical access time (% of SVP)
Svalbard	15	100 (12033 s/day)	30	100 (1805 s/day)
Tromsø	13	80	37*(37)	99 (99)
Fauske	13	76.6	34*(37)	87 (95)
Ørlandet	12	68.2	34*	77
Oslo	10	63.5	41*	87

*Table 5.2 Access time comparison for a sun-synchronous LEO satellite at 800 km altitude and 50% or less cloud coverage. *values from AROME MEPS, other values are from AROME Arctic. Optical access times are calculated as 50% of the geometric access time multiplied by cloud coverage value.*

Since the datasets for different conditions (cloud free and less than 50% cloud coverage) lead to opposite conclusions, it is not possible to determine whether a station in continental Norway will have more or less optical access time than a station at Svalbard.

6 Conclusions

Optical satellite communications to and from ground stations require clear line-of-sight between laser transmitter and optical detector. The High North cloud coverage for a selected area is investigated in this report to estimate the communications availability for optical Earth terminals. We have utilized three sets of data: twelve months of satellite images from satellites estimating the percentage of cloud coverage for a 1.6 km grid, SYNOP cloud cover observations in Norway and the AROME numerical weather models with 2.5 km grid.

There are significant deviations between the data sets with respect to estimated cloud coverage. It is noted that the observation types are not directly comparable and the Satellite data and AROME model cover different years. The differences are larges for the island locations of Svalbard, Bear Island and Jan Mayen.

Less cloud cover is observed over land, and island such as Svalbard and Greenland have significantly lower cloud coverage compared to areas in the open sea. The satellite images from 2014 give a maximum of about 33% cloud free conditions at the potential ground locations selected for. The values given by the AROME prediction models for 2018 are significantly lower than those from satellite images, especially at the island locations. The highest percentage of cloud free conditions is found in the southern Norway with values around 25%. However, when the comparison is done for cloud coverage of 50% or less the values for satellite images and model data agree much better, with very good agreement at the continental locations in Northern Norway.

Spatial earth station diversity has the potential of improving the availability. The availability improvements calculated using the two different datasets are similar and give about 20% improvement compared to a single location. The best two site combinations are found by combining Svalbard with Northern or Southern Norway, or Southern and Northern Norway. These combinations achieve 39-54% cloud free conditions, depending on the dataset. This is significantly less than an objective of having optical access to satellites during all passes. Interestingly Southern Norway combined with Svalbard is not significantly better than the other two combinations (Svalbard- Northern Norway or Northern-Southern Norway). Adding more locations does not improve the availability much further with only about 10% increase for a third station.

Temporal diversity was investigated using one dataset and found that given a longer observation period the probability of clear sky conditions at a single location increases by about 15% over 6 hours, 25% over 12 hours and 40% within 24 hours.

For LEO satellites the optical access time is a combination of a satellite being above the horizon and not obscured by clouds. For northern locations, the polar orbiting satellite is above horizon much more often so that the optical access time can be different even when the cloud coverage is the same. Simplified calculations could not determine with certainty whether an optical ground station will have longer optical access time at Svalbard or in the South of Norway since data for cloud free conditions and for 50% or less cloud coverage led to opposite conclusions.

A combination of several Norwegian diversity stations improves the access to satellites in the High North. However, the extent of the cloud coverage implies that diversity stations located in the same region (for example High North) will not ensure sufficient uptime for an Earth observation system perspective where data needs to be downloaded on each pass. Additional optical stations organized in an international network might be sufficient. Further studies are required to determine whether it is useful to include an Antarctic station for example at Troll. From a communications perspective the only way to ensure close to 100% data availability is to reduce the vulnerability to clouds by utilizing radio frequency communications between space and ground when necessary.

Appendix A Numerical weather maps

The locations utilized in the study are shown in Figures A.1 and A.2.

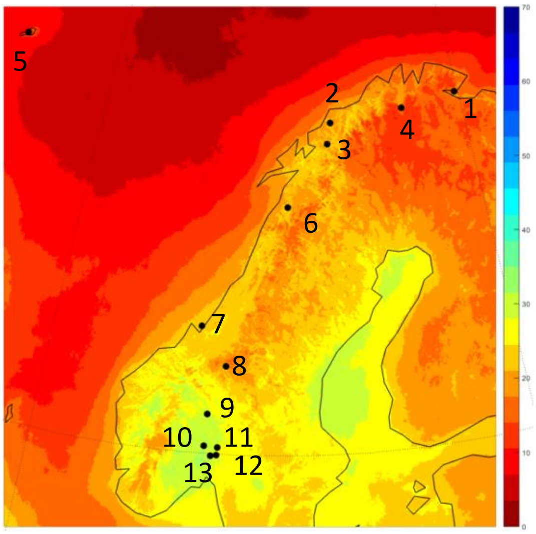


Figure A.1 *Locations used in the study shown on map with AROME MEPS data that shows% of time with less than 5% cloud coverage: 1-Vadsø (VAD), 2- Tromsø (TRO), 3-Bardufoss (BAR), 4-Porsangmoen (POR), 5 –Jan Mayen (JAM), 6-Fauske (FAU), 7-Ørlandet(ORL), 8-Røros (ROR), 9-Lillehammer (LIL), 10-Eggemoen (EGG), 11 –Gardermoen (GAR), 12-Kjeller (KJL), 13- Oslo (OSL).*

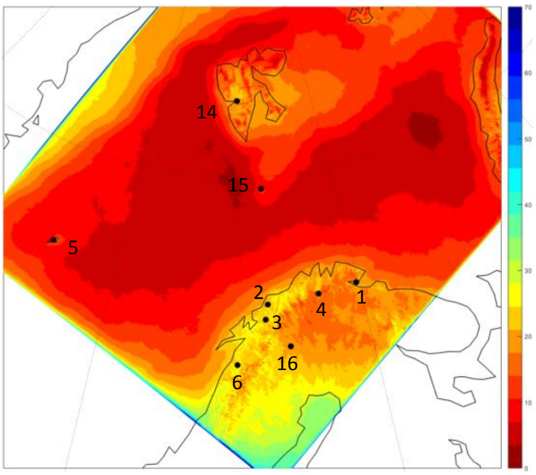


Figure A.2 *Locations used in the study shown on map with AROME Arctic data that shows% of time with less than 5% cloud coverage: 1-Vadsø (VAD), 2- Tromsø (TRO), 3-Bardufoss (BAR), 4-Porsangmoen (POR), 5 –Jan Mayen (JAM), 6-Fauske (FAU), 14- Svalbard (SVP), 15- Bear Island (BEI), 16- Esrange Kiruna (KIR).*

Appendix A.1 Spatial diversity for AROME data

Spatial diversity for cloud free conditions at 9 locations in the AROME Arctic area is given in Table A.1 and for 13 locations in the AROME MEPS area in Table A.2. For the Arctic area the values are quite similar for multiple combinations with typical improvement from single site of about 15%. For the MEPS area combinations involving a site in the south of Norway (Lillehammer, Eggemoen or Oslo) with one of three sites in the north (Fauske, Tromsø, Bardufoss) gives best results. Typical improvement over single site is about 20%.

	VAD	TRO	BAR	POR	JAM	FAU	SVP	BEI	KIR
VAD	15	29	31	21	23	31	25	20	26
TRO	29	19	26	25	26	31	29	23	29
BAR	31	26	20	26	27	31	30	24	29
POR	21	25	26	11	19	28	22	17	22
JAM	23	26	27	19	9	28	20	15	22
FAU	31	31	31	28	28	21	30	25	29
SVP	25	29	30	22	20	30	12	18	26
BEI	20	23	24	17	15	25	18	7	20
KIR	26	29	29	22	22	29	26	20	15

Table A.1 *AROME Arctic two-station diversity calculations for cloud free conditions (≤0.5% cloud coverage). Light red are the values for single station, green highlights 3 best combinations in each row.*

	VAD	TRO	BAR	POR	JAM	FAU	ORL	ROR	LIL	EGG	GAR	KJL	OSL
VAD	11	25	26	18	19	26	28	23	33	32	30	31	34
TRO	25	16	22	23	23	27	31	28	38	37	34	35	38
BAR	26	22	17	23	24	27	31	28	38	38	35	36	39
POR	18	23	23	10	18	24	26	22	32	31	29	29	32
JAM	19	23	24	18	8	24	26	20	30	30	27	28	31
FAU	26	27	27	24	24	17	30	27	37	37	35	35	38
ORL	28	31	31	26	26	30	19	25	36	36	34	35	37
ROR	23	28	28	22	20	27	25	13	30	31	28	30	32
LIL	33	38	38	32	30	37	36	30	25	33	32	33	35
EGG	32	37	38	31	30	37	36	31	33	24	28	29	30
GAR	30	34	35	29	27	35	34	28	32	28	21	25	29
KJL	31	35	36	29	28	35	35	30	33	29	25	22	28
OSL	34	38	39	32	31	38	37	32	35	30	29	28.1	25

Table A.2 *AROME MEPS two-station diversity availability probability, cloud free conditions (≤0.5%). Light red are the values for single station, green highlights 3 best combinations in each row.*

For less than 50% cloud coverage the spatial diversity results are given in Tables A.3 and A.4. Again for AROME Arctic area there are multiple combinations with very similar values. The typical gain from single site is 20% for mainland locations and 28–30% for island locations. For AROME MEPS it is again the group of stations in the south combined with stations in the north that give best results with improvement of about 30%.

	VAD	TRO	BAR	POR	JAM	FAU	SVP	BEI	KIR
VAD	35	55	56	48	49	56	54	47	53
TRO	55	37	48	50	51	52	56	47	54
BAR	56	48	37	51	52	51	57	48	52
POR	48	50	51	31	47	52	52	44	49
JAM	49	51	52	47	21	51	45	37	48
FAU	56	52	51	52	51	37	56	48	52
SVP	54	56	57	52	45	56	30	42	54
BEI	47	47	48	44	37	48	42	20	46
KIR	53	54	52	49	48	52	54	46	33

Table A.3 AROME Arctic two-station diversity calculations, 50% or lower cloud coverage. Light red are the values for single station, green highlights 3 best combinations in each row.

	VAD	TRO	BAR	POR	JAM	FAU	ORL	ROR	LIL	EGG	GAR	KJL	OSL
VAD	32	51	52	46	46	52	54	54	62	60	58	59	60
TRO	51	32	42	47	47	47	53	54	62	62	59	61	62
BAR	52	42	34	49	49	47	54	55	63	63	60	61	62
POR	46	47	49	31	47	50	52	53	61	60	57	58	60
JAM	46	47	49	47	20	49	49	47	55	54	51	52	54
FAU	52	47	47	50	49	34	51	53	61	61	58	60	61
ORL	54	53	54	52	49	51	34	48	58	59	56	57	58
ROR	54	54	55	53	47	53	48	33	53	55	52	54	55
LIL	62	62	63	61	55	61	58	53	43	52	51	53	53
EGG	60	62	63	60	54	61	59	55	52	42	48	48	48
GAR	58	59	60	57	51	58	56	52	51	48	38	43	45
KJL	59	61	61	58	52	60	57	54	53	48	43	40	45
OSL	60	62	62	60	54	61	58	55	53	48	45	45	41

Table A.4 AROME MEPS Two-station diversity availability probability, 50% or lower cloud coverage conditions. Light red are the values for single station, green highlights 3 best combinations in each row.

Abbreviations

Abbreviation	Explanation
AROME	Application of Research to Operations at MesoscalE
CDF	Cumulative Distribution Function
ECMWF	European Centre for Medium-Range Weather Forecasts
FMI	Finnish Meteorological Institute
HRES	Atmospheric Model high resolution 10-day forecast
LEO	Low Earth Orbit
MEPS	MetCoOp Ensemble Prediction System
METOP	Meteorological operational satellite
MOSCOM	Miltary Optical Satellite Communication
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
SMHI	Swedish Meteorological and Hydrological Institute
SYNOP	Synoptic
UTC	Universal Time Code

References

[1] Hamid Hemmati, “Deep Space Optical Communications,” Jet Propulsion Laboratory California Institute of Technology, 2005. [Online.] https://descanso.jpl.nasa.gov/monograph/series7/Descanso_7_Full_Version_rev.pdf

[2] Pål Bjerke, “Cloud influence on maritime surveillance by an optical satellite,” FFI-rapport 2015/02017. ISBN 978-82-464-2692-1. [Online.] https://www.ffi.no/no/Rapporter/15-02017.pdf

[3] Norwegian Meteorological Institute, “Frost,” [Online.] https://frost.met.no/index.html

[4] M. Rytir, M. Cheffena, P. A. Grotthing, L. E. Bråten and T. Tjelta, “Three-Site Diversity at Ka-Band Satellite Links in Norway: Gain, Fade Duration, and the Impact of Switching Schemes,” IEEE Transactions on Antennas and Propagation , Vol. 65, Issue 11, pp 5992 – 6001, 2017.

About FFI

The Norwegian Defence Research Establishment (FFI) was founded 11th of April 1946. It is organised as an administrative agency subordinate to the Ministry of Defence.

FFI's MISSION

FFI is the prime institution responsible for defence related research in Norway. Its principal mission is to carry out research and development to meet the requirements of the Armed Forces. FFI has the role of chief adviser to the political and military leadership. In particular, the institute shall focus on aspects of the development in science and technology that can influence our security policy or defence planning.

FFI's VISION

FFI turns knowledge and ideas into an efficient defence.

FFI's CHARACTERISTICS

Creative, daring, broad-minded and responsible.

Om FFI

Forsvarets forskningsinstitutt ble etablert 11. april 1946. Instituttet er organisert som et forvaltningsorgan med særskilte fullmakter underlagt Forsvarsdepartementet.

FFIs FORMÅL

Forsvarets forskningsinstitutt er Forsvarets sentrale forskningsinstitusjon og har som formål å drive forskning og utvikling for Forsvarets behov. Videre er FFI rådgiver overfor Forsvarets strategiske ledelse. Spesielt skal instituttet følge opp trekk ved vitenskapelig og militærteknisk utvikling som kan påvirke forutsetningene for sikkerhetspolitikken eller forsvarsplanleggingen.

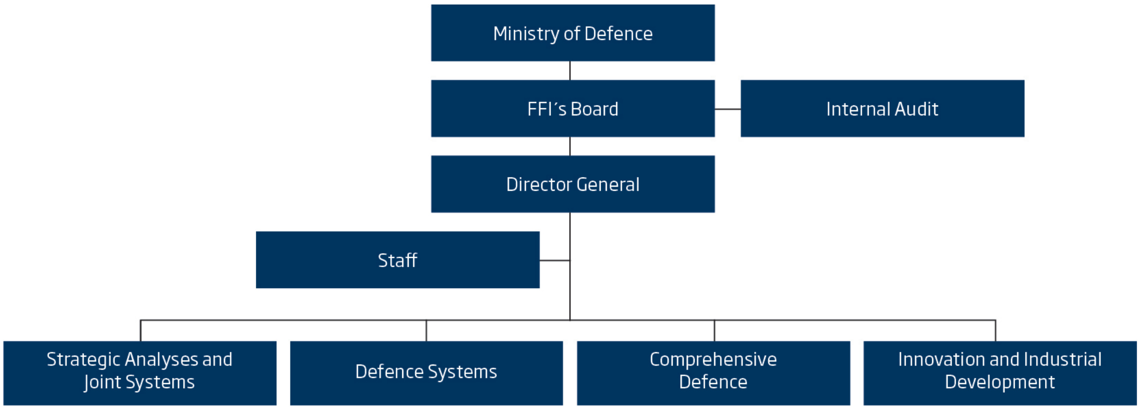
FFIs VISJON

FFI gjør kunnskap og ideer til et effektivt forsvar.

FFIs VERDIER

Skapende, drivende, vidsynt og ansvarlig.

FFI's organisation



Forsvarets forskningsinstitutt
Postboks 25
2027 Kjeller

Besøksadresse:
Instituttveien 20
2007 Kjeller

Telefon: 63 80 70 00
Telefaks: 63 80 71 15
Epost: ffi@ffi.no

Norwegian Defence Research Establishment (FFI)
P.O. Box 25
NO-2027 Kjeller

Office address:
Instituttveien 20
N-2007 Kjeller

Telephone: +47 63 80 70 00
Telefax: +47 63 80 71 15
Email: ffi@ffi.no

FFI Forsvarets forskningsinstitutt
Norwegian Defence Research Establishment