STUDY ON FOREST FIRE DETECTION WITH SATELLITE DATA

Mathias Milz
Avdelning Rymdteknik
Institutionen för System- och rymdteknik (SRT)
Luleå tekniska universitet
Kiruna

March 8, 2013

LULEÅ TEKNISKA UNIVERSITET

1 Introduction

Countries in Scandinavia are to large extends covered by forest and it characterizes the Scandinavian landscape. In Sweden, about 65 % of the area are covered by forests. The forests are an important cultural heritage and play a big role in the people's lives. Scandinavia is famous for the vast areas with undisturbed nature and the according wildlife. The forests provide a basis for animals which need large territories for life and hunting. Only few regions in Europe can provide habitats for moose, wolves, bears, and other animals with strong territorial needs.

The wood and paper industries in Sweden and Finland are an important player in the national economy. In certaion areas, these are major employers. These industries are very sensitive to changes in the forest extends and structure.

Furthermore, the forests play an important role in people's leisure activities. The life in Scandinavia and especially in the rural areas is closely related to nature with lakes and forests. Activities such as hiking, fishing, and hunting are major activities in the leisure time.

The Scandinavian forests are an important part of the landscape and the culture in this region. The economy and society depend on the forest and are sensitive to incidences which destroy forests. Small and large area of forests can be damaged or destroyed by severe weather situations (e.g. the storm "Gudrun" in January 2005), by pest infestation or, especially during summer, forest fires. For some incidences, like storms, the prevention or recognition in an early stage is difficult. On the other hand, for other incidences, like pest infestation and especially forest fires, early detection can help to reduce the damages and the affected area significantly. This study deals with the detection of forest fires by using satellite borne remote sensing techniques.

2 Forest fires in Sweden

The Landscape in Sweden is dominated by forests. These forests have, depending on the regional climate and usage different composition and structures. The location of Sweden, at mid to high latitudes has a significant influence of the Atlantic ocean and the influence of the weather regimes of the midlatitude westerlies. These influence factors provide conditions which usually suppress the development of large and strong forest fires due to the high humidity and related rain rates. But due to the variations in forest structure, surface and local climate, the risk for forest fires can increase locally. Especially during the summer season after warm and dry periods the risk for forest fires increases. During summer, a continuous observation of the conditions in the forest areas such as humidity of the surface, grass, bushes and trees together with the weather conditions provide information on the risk of forest fires.

The Swedish introduced a classification of the forests with respect to the frequency of fires, the ASIO (A(ldrig),S(ällan),I(bland),O(ofta) classification, which provides a first generic assessment of the forest fire risk in Sweden (*Hansen*, 2003).

Beside the assessment of the fire risk, early recognition of fires is crucial to minimize the ecological and economical damages. Continuous observations during the forest fire season and especially under conditions with increased risk are important for early intervention. In Sweden, the observation of the forest covered areas is challenging. In regions with comparatively high population density, the detection of a larger number of forest fires can be expected to come with comparatively short notice as fires are probably close enough to towns and settlements that attentive people and authorities can recognise the start of a fire within reasonable time. However, during certain periods, e.g. night time or times with reduced bustle in the affected area, the detection of fires can be significantly delayed and the fires can spread and become dangerous. In Sweden and Scandinavia in general, there are many regions with forests in sparsely populated areas. Here, the distances between the settlements inhibit any recognition of fire development without existing surveillance system. Authorities are aware of this lack of surveillance and run certain activities and also search for new solutions for surveillance of these regions.

One possibility is the use of ground based observation systems. E.g, a network of cameras for the detection of fire and smoke. For certain areas, such systems can work, but their performance depends on the circumstances. In structured terrain, an increased number of cameras is required to cover an area, which, among others, increases the costs. Under conditions with decreased optical visibility, their performance can be reduced. Additionally, the surveillance has to be continuously either using automatic detection systems or human operators. The costs for such systems are comparatively high. Often, the camera based surveillance of the observations is not conducted by the affected authorities, but done by companies which sell these services. This is an additional cost factor and introduces further risks for the alarm system. Sweden does not operate such ground based optical surveillance systems.

Airborne surveillance has been performed for several years. The Swedish authorities are aware of the importance of airborne surveillance of forest fire to prevent late recognition, especially in remote areas. However, the individual county authorities decide on the use of airplanes and the Swedish Civil Contingencies Agency (MSB) covers the costs. For some counties, a system of voluntary airborne surveillance has been established. Private persons and air clubs are connected via voluntary air surveillance networks.

The current available airborne and ground based systems and methods provide valuable observations. However, these systems are comparatively expensive and need a certain amount of human work power for operating the systems and airplanes and analysing the data. These classical methods are useful in times and regions with increased forest fire risk, but a continuous observation is comparatively expensive both, with respect to resources and financially.

During the last decades, a large amount of earth observing satellites have been operated for different purposes. Among others, meteorological satellites with instruments, which are sensitive to the high temperatures related to e.g. forest fires are currently in polar orbits. The meteorological satellites submit their data directly to receiving stations during their overpass. Meteorological services use these data for short term forecasts. The methods used for meteorological purposes are similar to methods required for forest fire detection. Thus these satellite observations, using existing infrastructure at e.g. weather services, can provide a good and comparatively cheap tool for forest fire detection and short term notification.

3 Satellite borne detection of forest fires

With the development of operational Earth observing satellite platforms useful tools, are provided for continuous surveillance of the Earth. Depending on the orbit properties, observation technique and platform properties, information on the state of the atmosphere and Earth surface can be available within very short timescale for most locations on the earth with reasonable good resolution. There are many different instruments on board various satellites which are used for different purposes. Sensors in the visible (VIS), near Infrared (NIR) and mid infrared region (MIR) (approx. 0.3-1.1 μm: VIS/NIR, 3 - 15 μm: MIR) have been used for observations of the vegetation for quite a while. Combinations of different channels or spectral regions can be used to get information on the state and the health of the vegetation. E.g. the dryness of the vegetation can be observed and included in fire risk analysis or, after larger forest fires this information can then be used to obtain information about the burned area to estimate damages.

Some of the satellite instruments e.g. on satellites of the Landsat and SPOT series are designed for high resolution imagery of the Earth's surface. However, their products require a certain amount of postprocessing before they are delivered to the customers. These products are very useful for surveillance for changes over longer timescales and provide assessments for changes even for smaller areas.

The US weather service NOAA (National Oceanographic ans Atmospheric Administration) and the European Eumetsat run a set of operational satellites with sensors in the above mentioned spectral regions. These satellites are operated in sun-synchronous orbits and geostationary orbits and provide continuous global observations. As these observations are required for accurate weather forecasts on short timescales, the data from these platforms are usually available and processed within short time after the observation and available via various dedicated distribution channels. As will be shown below, the MIR channels of instruments on these satellites can be used for the near-real-time (NRT) detection of forest fires.

Satellites on geostationary orbits are placed at a distance of about 36 000 km above the Equator. This orbit allows a period of 24 hours and the satellite appears to be stationed above a certain fixed point at the equator. These orbits have the benefit that every image of the satellite is taken of the same scene at different times. For the VIS and IR instruments on these satellites, typically one image is taken every 15 minutes (Meteosat Second Generation). This rate provides unique opportunities for the early detection of fires and the observation of the development of the fires. Images from geostationary satellites are used for fire detection and observation for tropical and subtropical regions and mid-latitudes up to approximately 40-45° N/S. However, due to the long distance from the Earth, the resolution is limited. The data are among others used by organisation for the detection of fires in Brasil, the USA and mediterranean countries in combination with observations from polar orbiting platforms and other sources.

For higher latitudes such as for the North European regions the use of geostationary satellites is inappropriate. The measurements suffer increasingly from the observation geometry.And, as a consequence of the increasing incidence angle of the line of sight, the ground-pixels become very large and the influence of the increased atmospheric path introduces quite high uncertainties. The observation of forest fires, considering the typical size of forest fires in Northern Europe, is not possible. Therefore, this study concentrates on the usage of polar orbiting satellites.

3.1 Polar-orbiting satellites

European and US agencies currently operate 7 operational meteorological satellites and additionally 3 scientific satellites wich provide observations which can be used for the detection of forest fires. These platforms are operated on so-called sun-synchronous orbits which means, that their orbit is chosen in a way that allows observations at a certain time of the day. The orbit inclination is selected in a way that the satellites overpass at the equator is always at the same local time at the equator. This overpass time defines the orbit of the satellite e.g. as “morning” or “afternoon” satellite. The local overpassing time is of course not only fixed to the equator but also for all other latitudes which means that the satellite will always pass over a certain latitude at a certain local time. Due to the orbit properties, the satellites usually do not pass over the same location every day but with a certain known repeat cycle. For NOAA-Satellites the repeat cycle is around 11 days or longer. However, the scanning geometry of the VIS/IR Instrument AVHRR and the corresponding instruments on other satellites scan a swath with a width of approximately 2500 km. This means that a place at middle or high latitudes is observed 2 to 4 times per day by each satellite. The observations are usually done within a few hours around the typical local time of the overpass at that latitude, which is defined for the sub-satellite track under the satellite.

Operational meteorological satellites currently in orbit are NOAA 15, NOAA 16, NOAA 17, NOAA 18, NOAA 19, MetOp A, MetOp B. Additionally, there are the scientific satellites Terra and Aqua of the NASA Earth Observation System (EOS) and the experimental satellite SUOMI which is a precursor for a new generation of meteorological satellites.

The various satellites are placed in different orbits offering observations during different times of the day in order to provide measurements for the operational weather forecasts. This means that locations in Scandinavia are typically observed several times throughout a day by various instruments. To illustrate the observation frequency and times, a location was selected in the center of Sweden located at 60 ° North and 15 ° East. Assuming an instrument, scanning with off-nadir angles of 45 ° to both sides of the flight path, all possible observations of this location during July 2012 have been evaluated. According to *Rauste et al.* (1997), during their study period typically 4 to 8 satellite overpasses per day were possible.

In Fig. 2 the observation times for this location are displayed for every day in July 2012 for the the operational satellite NOAA-16. For the other satellites similar figures are shown in App. A . Additionally, a histogram with the number of observations during this month separated for individual hours of the day (local time) is shown in Fig. 3. As can be seen, several observations at different times per day are available which, under suitable conditions can observe possible forest fires.

Channel	Band (μm)	region
1	0.58 - 0.68	reflected sunlight
2	0.725 - 1.1	reflected sunlight
(3 A)	1.58 - 1.64	reflected sunlight
3 (3 B)	3.55 - 3.93	reflected sunlight/emitted IR
4	10.5 - 11.3	emitted terrestrial radiation
5	11.5 - 12.5	emitted terrestrial radiation

Table 1: Channel numbers, Band-range, and origin of AVHRR channel data. For some instruments, channel 3 is split into two channels 3A and 3B (source: http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html)

3.2 Advanced Very High Resolution Radiometer (AVHRR)

One of the core instruments on board NOAA and MetOp satellites is the "AVHRR" (Advanced Very High Resolution Radiometer). AVHRR has 5 channels in the VIS/IR which are, among others, used for the detection of surface temperatures and clouds. The spectral channels of AVHRR are listed in tab. 1

AVHRR is a nadir-looking instrument, which means that the instrument is looking on the Earth directly under the satellite. The instrument is scanning perpendicular to the flight path (across-scanning) and covering angles from the nadir (nadir angle 0 °) to off-nadir angles up to 55 ° to each side of the flight-path. This scanning-method provides a swath with usually 2048 pixels across the flight path. The resolution at nadir is around 1.1 km and the effective swath width is wider than 2500 km. Towards the edges of the swath, the resolution becomes poorer (approximately 2 km × 6 km) and the influence of the atmosphere on the observation increases due to the measurement geometry.

According to Wien's displacement law, the wavelength of the maximum emitted radiation is determined by the temperature of the radiation source. For sunlight, this maximum is around 600 nm, corresponding to the Sun's surface temperature of around 6000 K. The typical temperature range of the Earths surface and atmosphere, lead to a maximum of the radiation intensity at around 10 μm. For temperatures which are typical for open fires, (600 to 1200 K) the maximum radiation intensity is situated at wavelengths around 3.7 μm. The position of infrared channels around 3.7 μm suggest, due to their position close to the maximum of radiance for open fires, to use these channels for the detection of open fires.

3.2.1 Information-content of Channel 3 (3.7 μm)

The sensitivity of channels around 3.7 μm to forest fires on satellite borne remote sensing instruments has been shown by *Matson and Dozier* (1981) using examples from AVHRR instruments on the satellites of the TIROS series. This feature has been applied for the detection of forest fires with operational sensors by *Kaufman et al.* (1990). They describe the use of AVHRR channel 3 for the detection of forest fires and most of the algorithms used by various institutions and organisations are based on the method described here.

However, for AVHRR the performance of channel 3 shows certain properties which have to be considered in the application of the data for fire detection. Channel 3 has not been designed for fire detection. The detector characteristics are intended for the application of solar and terrestrial radiation and is sensitive to changes in both sources. The response of the detectors was designed for radiances corresponding to typical values of solar and terrestrial radiation. For brightness temperatures (The black body radiation corresponding to this temperatures according to Planck's law) above approximately 50 ° C or ca 320 K, respectively, the AVHRR channels 3 become saturated (*Matson et al.*, 1987). This means the recorded signal will not increase for radiations related to higher temperatures or stronger reflection of solar radiation.

This leads to the following problems related to channel 3 application for fire detection:

fire area For typical fire temperatures (500 - 1000 K) already small fires (0.02 % of the pixel area or 0.1 to 0.5 ha) can saturate the pixel value. However, as long as sun-heated surfaces and reflected sunlight can be excluded, this is a good indicator for fire occurrence in the pixel.

bare soil areas/mountains The sunlight can heat bare surfaces (mountains, bare soil) which reach sufficient high temperatures under warm summer conditions. The observed signal in channel 3 cannot be distinguished from forest fire signals. However, for boreal regions, this problem is of minor importance. Bare soil areas here often are smaller than the AVHRR pixel size and the mean surface temperatures in the scanned area usually does not reach such high levels (*Rauste et al.*, 1997).

reflected sunlight The region around 3.7 μm is also sensitive to reflected sunlight. During day-time specular reflection from larger areas with high reflectivity can lead to strong signals up to the detection limits. This ambiguous signal cannot be separated from wild fires. This problem can be avoided by restriction of the detection to night time observations, which is not desirable as most fires start during day-time *Rauste et al.* (1997). Another alternative is to exclude parts of the observations with observation angles which are close to angles of specular reflection of sunlight in order to avoid misinterpretation.

Under night time conditions, AVHRR channel 3 observations can be used to detect forest fires, as the most important error sources can be neglected. However, the use of additional information from the other channels can help to improve the reliability.

3.2.2 Use of additional AVHRR channels

The above described properties of channel 3 (3.7 μm) restricts the application of these observations to certain conditions, e.g. night time observations. By including observations from other channels, namely channels 2 (0.7 - 1.1 μm) and 4 (11 μm), it is possible to filter out certain conditions and extend the detection range to daytime measurements as described by *Kaufman et al.* (1990).

In the following we list criteria which are used to filter the data and exclude erroneous observations:

$\mathbf{T_{B,3} \geq 320}$K The signal in channel 3 is high, e.g. beyond the saturation limit of 320 K (See e.g.(*Li et al.*, 2000)). This criterion is the key information on forest fires as the signal is detected by the fire-sensitive channel 3.

$T_{B,3} - T_{B,4} \geq 15$K Comparison of the observed radiances between channel 3 and 4 in order to assure that the observed signal is a fire and not a warm surface. Channel 4 is located in the thermal Infrared around the window region at 11 μm and is sensitive to emissions corresponding to typical temperatures from the surface and atmosphere. If the surface is too warm, e.g. due to strong solar irradiation, the pixel is masked to avoid misinterpretation.

$T_{B,4} \geq 295$K The surface has to be sufficiently warm to assure that the pixel is not only dominated by cloud signals.

Reflectance Ch 2 $\leq$ 16% The reflectivity in the visible range as seen from the satellite above the top of the atmosphere (TOA) has to be sufficiently low in order to reduce the risk for ambiguous solar signal detection in Channel 3.

Additionally, some other requirements for the observations have to be fulfilled. The observation should be sufficiently far from the edge of the swath. Therefore one requirement is that the observation pixels should be more than 100 pixels away from the edge of the swath (*Rauste et al.*, 1997). Regions around anthropogenic heat sources such as larger industry areas or oil plattform should be excluded from the detection area to avoid erroneous fire detection.

Issues related to false detection due to warm surfaces is limited under Scandinavian conditions. In order to heat up larger surface areas, these have to be either bare soil or very dry grassland or harvested cropland. These conditions may apply during warm and dry periods towards the end of the typical forest fire seasons or in the planes in Southern Sweden

3.3 Moderate Resolution Imaging Spectroradiometer (MODIS)

Another instrument with channel characteristics suitable for forest fire detection is MODIS (Moderate Resolution Imaging Spectroradiometer) on board the American EOS Aqua and EOS Terra satellites. Terra and Aqua are so-called research satellites with the aim of long term monitoring. However, the data are disseminated in a way that makes it possible for weather services to access the data directly during the overpass of the satellite. Therefore, the data from these instruments can beof interest for the surveillance of forest fires.

The MODIS mid-IR channel around 3.7 μm is slightly moved compared to AVHRR. This is to reduce influence by water vapour absorption and to reduce sun-light reflectance. The channels are listed in Tab. 2.

The resolution of MODIS is in the range of 1 km, similar to AVHRR, but complementary channels are partly of higher resolution and can therefore provide different information. Also the scanning pattern is quite similar and covering a similar range during the satellite's overpass.

The channel setup for MODIS is comparable to the ones of AVHRR and therefore it is possible to adjust the AVHRR algorithms to these date. When combining AVHRR and MODIS, it is important to apply consistent methods to keep the detection of forest fires comparable and include them in a common system.

channel	Band width (μm)
1	0.620-0. 670
2	0.841- 0.876
6	1.628- 1.652
7	2.105-2.155
8	0.405- 0.420
20	3.660- 3.840
21	3.929- 3.989
22	3.929- 3.989
31	10.780- 11.280
32	11.770- 12.270

Table 2: Channel number and spectral region of MODIS channel data and primary target parameters. (source: http://modis.gsfc.nasa.gov)

Additionally to the originally measured data, NASA provide the more sophisticated data products MOD 14 and MOD 40 which detect thermal anomalies and are sensitive to fires and biomass burning. These products are level 2,3 or 4m which means their processing is more advanced and therefore not distributed directly from the satellite but via dedicated processing centers. MOD 14 is delivered once per day and therefore only of limited interest for NRT fire detection. However, these products can be of interest for the analysis and assessment of the detected hot spots and the reliability of the forest fire detection.

3.4 Visible Infrared Imaging Radiometer Suite (VIIRS)

A new instrument which has recently been launched is VIIRS (Visible Infrared Imaging Radiometer Suite) on board the polar orbiting satellite Suomi. The channel setup with channels around 3.7 μm and 4 μm and other channels in the VIS-NIR and thermal infrared regions, similar to the regions used by AVHRR, are suitable for forest fire detection using algorithms similar to those for AVHRR and MODIS. Initial results show that the VIIRS channels around 3.7 and 4 μm are suitable for forest fire detection (see Fig. 1)

SUOMI is a precursor satellite for a new generation of operational meteorological satellites. For reasons of continuity, the instruments suite is similar to the current familiy of operational satellites but not yet considered as operational.

3.5 Other satellites

Several other countries, such as Russia, China, and India operate Earth observation satellites with instruments using similar channels as AVHRR. It is unclear to which extent these countries provide access to the data, especially under operational conditions as the NOAA and MetOp series which means direct downlik from the satellite during its overpass. China is operating a similar polar orbiting sun-synchronous satellite, the FY-1 and FY-3 series with VIS/IR instruments on board. Here, a usage can be of interest, if the satellite orbit data and instrument data can be accessed continuously and online during

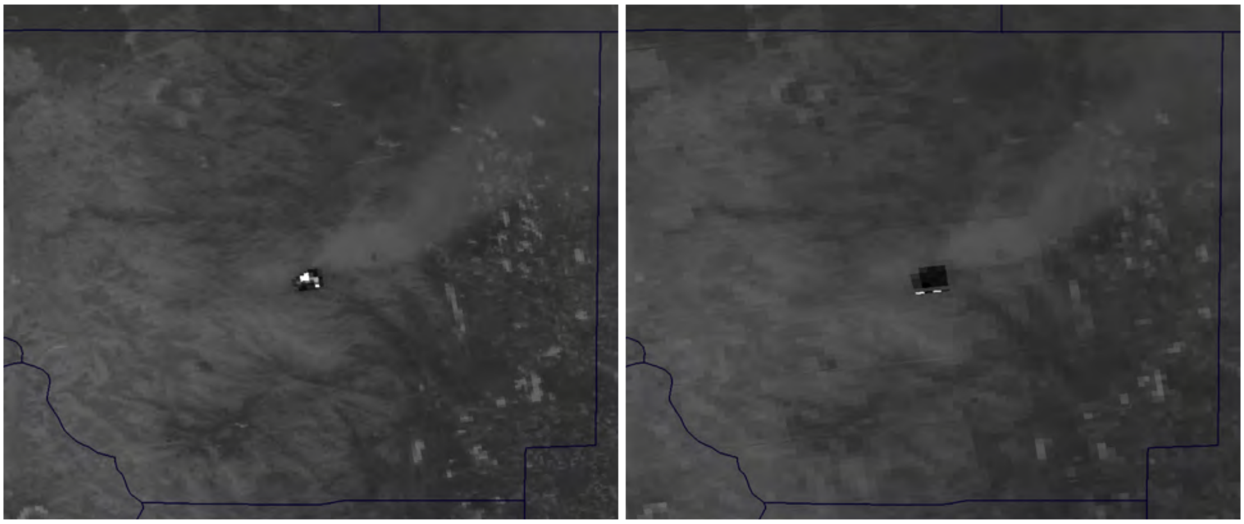

Figure 1: Forest fire on 2012-06-09 as seen by the VIIRS I-04 and M-12 channels situated around 3.7 μm Daily. (Courtesy: Curtis Seaman, CIRA. Source: http://rammb.cira.colostate.edu/projects/npp/I04_saturation_High-Park-fire.pptx)

the satellite overpass.

3.6 Limitations of VIS/IR detectors

Earth observing systems operating in the visible and infrared spectral region are sensitive to atmospheric conditions. The channels used for the detection of forest fires as described, are sensitive in so-called window regions. Under cloud-free conditions, the radiance reaching the sensors has been emitted or reflected from the Earth's surface. But sensors in the VIS and IR region are very sensitive to the influence of clouds in the field of view. Thin cirrus clouds can be semi-transparent in the VIS and in the infrared region. These clouds weaken the signal emitted from the Earth's surface due to the extinction. Depending on the thickness, the requirements for the detection of a fire defined above may no longer be fulfilled. The same is valid for the case of small scale clouds within the field of view which can cover the hot spots partly.

Depending on the weather conditions, these clouds can move with time and a subsequent satellite overpass may detect the fire. If the clouds are of larger scale and long lasting, this method might fail. However, under these conditions with increasing cloudiness also the chance for precipitation might increase. Here a possible tool could be to use cloud products obtained from the same instruments which could provide information on the cloud fraction and the variability of the observations.

There are other sensors on these satellites which are less sensitive to the influence of clouds. Such sensors operate for example in the microwave region. But the sensors operating in these spectral regions have a comparatively poor horizontal resolution with ground pixels with a diameter of around 15 km at nadir. Additionally, the sensitivity to forest fires is very small as the spectral response to changes in surface temperature is comparatively weak and the fires would have to be quite large to be detectable.

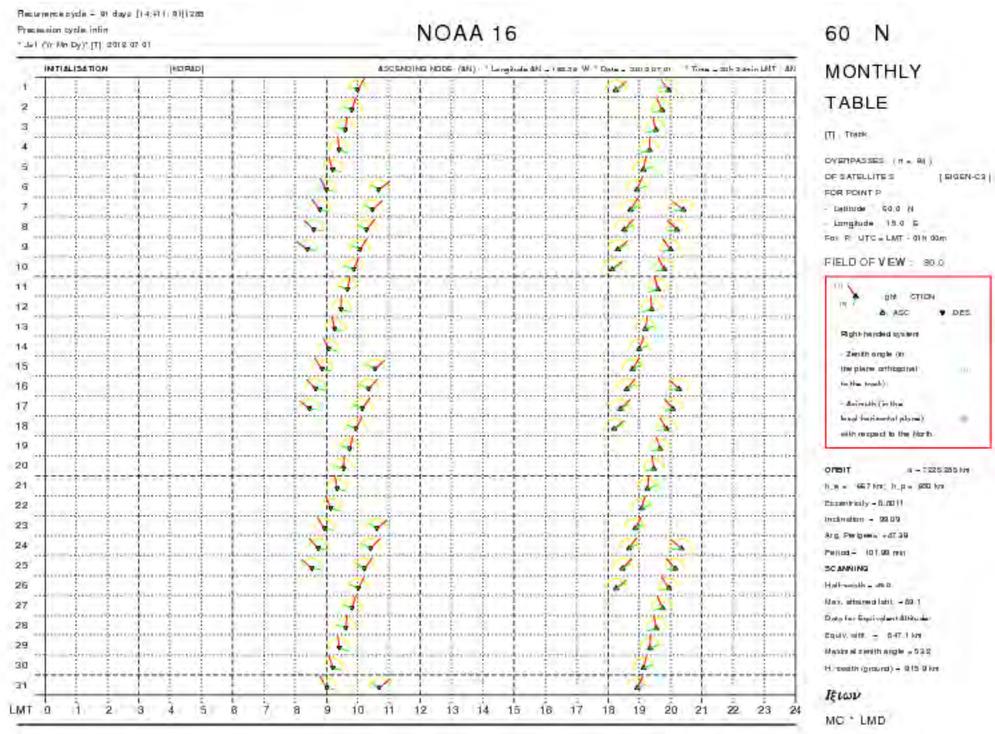

Figure 2: Daily local times for July 2012. Every marker provides the time and angle of observations of a point with the coordinates 60.00 N, 15.00 E, representing central Sweden, with NOAA16, allowing observations with off nadir scan angles between 0° and 45° to each side of the flight track(Graphic produced using:http://climserv.ipsl.polytechnique.fr/ixion.html

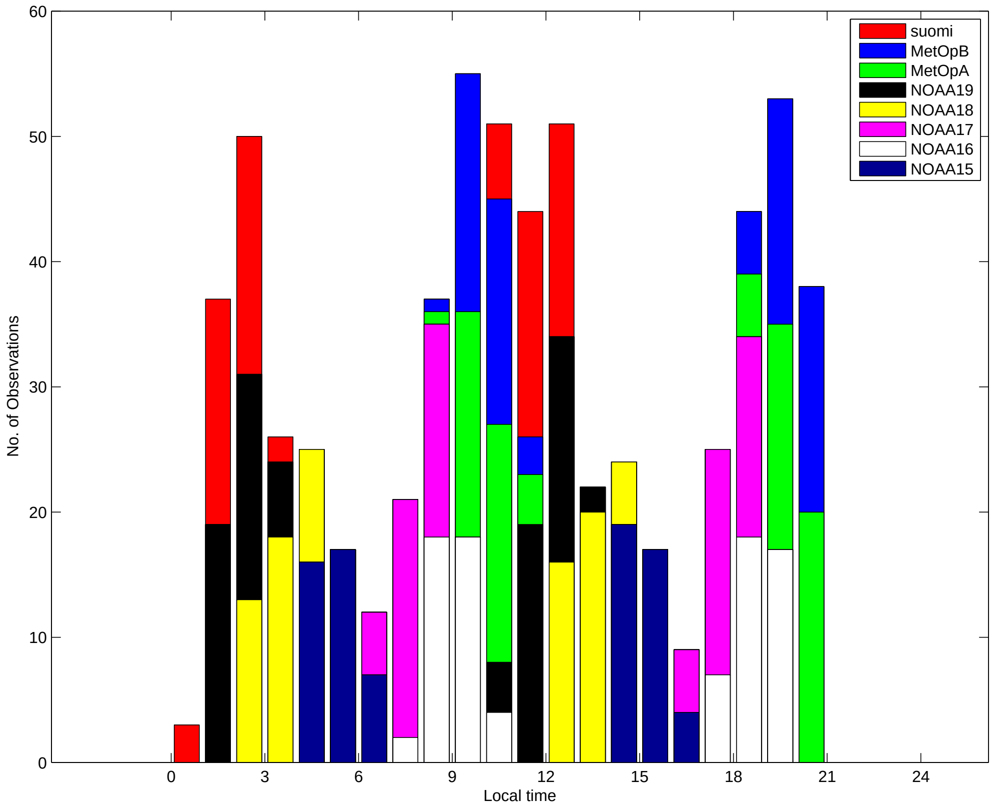

Figure 3: Histogram showing the number of observations of a point in central Sweden (60N, 15E) during July 2012 with possible observations for Sweden for every time of the day. The length of the bars is the total number of observations per hour. The individually coloured parts show the number of observations per satellite.

3.7 Organisations applying satellite-borne forest fire detection

The benefit of satellite-borne detection of forest fires and the subsequent surveillance is obvious and several countries and regions with high risk of forest fires use these methods. Since forest fires are a global issue and countries all over the world are threatened by them, a coordinated global network on the satellite borne surveillance of forest fire related has been established. The GOFC/GOLD (Global Observations of Forest and Land Cover Dynamics) is part of the Global Terrestrial Observing System (GTOS). The GOFC/GOLD Fire Monitoring and Mapping Team links regional self-organized networks working with the detection and monitoring of forest fires an is partnering with the Global Fire Monitoring Center (GFMC) , and the United Nations International Strategy for Disaster Reduction (UNISDR) Wildland Fire Advisory Group / Global Wildland Fire Network. (Source: http://gofc-fire.umd.edu) These organizations are umbrella organizations for regional and country-specific centers applying forest fire detection.

The US national weather service NOAA provides the FIMMA product (Fire Identification, Mapping and Monitoring Algorithm) which uses AVHRR based data obtained by the above method described above. These data are among others used by the Hazard Mapping System (HMS) Fire and Smoke Product, which combines several forest fire and smoke related data sources to get a nation wide overview on the fire situation in the US. HMS is also using data from MODIS, VIIRS, and data from sensors on geostationary satellites of the GOES series since most of the fire threatened areas are far enough south to allow the usage of geostationary sounders.

The Canadian Wildland Fire Information System (http://cwfis.cfs.nrcan.gc.ca) also uses data based on the previously described methods using AVHRR and MODIS. The Canadian and US services offer broad information related to forest fires. Besides monitoring of the current state and the early detection of hot spots, they also offer estimates of the current risk of forest fires and forecasts to estimate the risk for the near future in order to provide a basis for preparation for affected authorities.

In Europe "the European Forest Fire Information System (EFFIS) supports the services in charge of the protection of forests against fires in the EU countries and provides the European Commission services and the European Parliament with updated and reliable information on wildland fires in Europe." (http://effis.jrc.ec.europa.eu). EFFIS was established by the JRC (Joint Research Center, Ispra, Italy) and the Directorate General for Environment of the European Commission in collaboration with EU member states and associated countries. EFFIS collects and provides forest fire related data and information on pre-fire to post fire levels. The services are on a level that provides fire danger forecasts, evaluation and statistics for the various authorities. They even provide up to date information on hot spots which could be related to forest fires. However, these informations are on a higher intergovernmental level with various administrative levels between and within various countries.

The use and advantage of satellite borne forest fire detection relies an a system which allows a fast activity-chain covering the detection of a possible forest fire, the messages to the affected authorities and the regional dispatch centers, and notification of responsible fire stations in order to act immediately.

Several countries, especially in forest fire threatened areas such as the mediterranean region or the dry regions of North America, have such operative systems. However, the high latitudes and special conditions in Scandinavia require certain consideration for establishing such an information system. In Finland, VTT, the technical research center of Finland, in collaboration with the Finnish Meteorological Institute (FMI) established Forest Fire alert service using polar orbiting operational satellites which were presented above.

4 Forest fire detection in Finland

The Finnish Institutions VTT and FMI use satellite data from various operational meteorological satellites for the near real time detection of forest fires and subsequent submission of warnings to various authorities. Since the 1990ies observations of the advanced very high resolution radiometer (AVHRR) on board of the NOAA operational meteorological satellites are used for fire detection. This is mainly based on observations with channels around 3.7 μm which have high sensitivity to forest fire conditions. The prototype at VTT was first applied in 1993. Since 1994, the VTT/FMI fire detection has been operated during all forest fire seasons (spring until late summer). In subsequent years, other satellite instruments with similar channel characteristics which allow the detection of forest fires have been operational. VTT and FMI included observations from the MODIS instrument. For a study, observations from the ESA (A)ATSR instruments were also includes, but the studies showed that the ESA (A)ATSR observation were not useful for the fast detection of forest fires, due to technical reasons, namely a delay of up to several hours between observation and data delivery. MODIS data and AVHRR data are obtained with sufficient short times regarding delivery and processing that these data are currently used for the fire detection. In the section 4.1 the technical solutions are presented and discussed.

4.1 Technical solutions

In this section the technical solutions which are used to process the data are described. Most of the parts have already been described above and here the specifications will be described.

4.1.1 AVHRR

VTT developed the algorithm to detect forest fire signals in the observed scenes from overpassing satellites using the AVHRR instruments. The method is based on the principles presented above but with the following settings:

Channel 3 is saturated: $T_{B,3} \geq 320$K

Comparison with Channel 4 : $T_{B,3} - T_{B,4} \geq 15$K. This step excludes warm surfaces without forest fire.

$\mathbf{T_{B,4} \geq 295K}$ Exclude that the pixel is dominated by cloud signal.

TOA reflectance Ch 2 $\leq 16\%$ The reflectivity in the visible range has to be sufficiently low in order to reduce the risk for ambiguous solar signal detection in Channel 3.

Exclude specular reflection: The angle between incoming sunlight and the satellites view line has to be sufficiently far away from the angle od direct reflection to avoid the risk of mis interpretation of solar reflection.

Exclude furthest off nadir pixels: The outermost 100 pixels of the scan line are excluded from the detection. The observation angle with the consequence of an increasing size of the ground pixel area and increasing influence of the atmosphere reduce the quality of these measurements and the risk of mis interpretation.

Exclude pixels around known industrial sites: Industrial sites, such as the large steel factory SSAB in Luleå are excluded from the detection as these often are source for increased temperature due to exhausts, large buildings which are heated by sun light or reflect suns light. A required distance of 20 km has been selected as this distance even excludes problems during the geocoding, when the satellite scene is corrected to agree with the geographical maps.

The procedures applied at FMI are among others described in *Rauste et al.* (1997); *Kelhä et al.* (2003, 2001)

4.1.2 MODIS

The data from MODIS are processed by FMI, with an algorithm comparable to the one used for AVHRR. Of course, minor adaptions had to be made in order to consider instrumental properties when producing a wildfire product based on MODIS. The MODIS wildfire product is based on MOD03 and MOD021KM products.

4.1.3 Satellite data availability and processing

FMI has satellite receiving stations which receive the data from the operational satellites with AVHRR and MODIS as soon as they pass over the region and have direct contact to the receiving stations. As these data are important for the weather forecasts and especially for short term prognoses, they are processed immediately. This means that the observations are available and processed within a short time after the satellites overpass. Typically a forest fire alert can be sent within 25 minutes after the observation.

Both, the algorithm processing the AVHRR data and the one processing the MODIS data are running on the computer systems at FMI. The algorithms are comparatively fast and require only comparatively little resources on the computing systems.

4.1.4 Distribution of fire messages

As soon as the algorithms observe a possible forest fire, a message is created and distributed to the affected authorities, so-called Regional Dispatching Centers. These messages are sent as emails containing the information of the fire such as position and time of the first detection. An example for a typical email message is shown in Fig. 4. As forest fires usually last longer, the message with the detected fire is only sent out after the first detection. This is to prevent a flood of messages and to reduce the risk of misinterpretation or unintended ignorance of a new fire.

Together with the message of a detected forest fire, VTT/FMI request feedback and verification of the detected fire. The user is requested to confirm the fire or mark it as erroneuos detection. Additionally, the information on the type of fire can be provided, e.g. if it was a real forest fire (together with additional data such as size and duration), if it was prescribed (also with additional data such as burnt area), or if it was another type of fire or heat source (e.g. industrial sites). Of course, response is requested even if the fire was not real. These feedback informations are collected and analysed to obtain a statistical overview on the performance and reliability of the fire detection system and on the temporal and spacial distribution of various types of fire during the forest fire season. After the forest fire season, these analysis are gathered and summarized in a report which is delivered to the ministry of interior in Finland.

The analysis of the detected forest fires in the recent years provides information on the reliability of the system. For the years 1999 and 2000 when the system was part of an ESA project, an error rate of around 12 % false alarms was analysed, where the highest rate was about 16 % in Finland (8 false detections out of 53 observations). These values were based on the feedback rate by the different countries which were included in the message system. The highest confirmation rate was provided by Sweden, Estonia and Finland.

Currently, The Swedish Civil Contingencies Agency (MSB) receives such messages as soon as fires are detected on Swedish territory or close to the borders. However, currently MSB does not have a dedicated distribution network to inform the Swedish regional dispatching centers and alarm centers. The information is not yet used in an appropriate way.

4.1.5 Requirements for forest fire detection

During the development of the forest fire detection algorithm, VTT, set up a list of user requirements which to a certain extent can be fulfilled. According to *Rauste et al.* (1997) these requirements are:

- The alert message should reach the local fire control authorities as soon as possible
- As many fires as possible that are active during a satellite overpass should be detected
- The fires detected should not include false alarms (error rate around 10%)
- The location of the fires should be detected with an accuracy of 1 - 2 km

The goal to reach the regional dispatching centers as quickly as possible can be delayed by some factors (*Rauste et al.*, 1997) :

- **Growth delay:** The time from the ignition of the fire until it became large enough to be detected

FIRE ALERT MESSAGE FROM AN EXPERIMENTAL
SATELLITE BASED FIRE MONITORING SYSTEM

Dear Forest-fires_Norway,

A possible forest fire has been detected.
http://virpo.fmi.fi/metsapalo_public/firemap/png/n161204301742_faxe0.png
Co-ordinates:
Latitude(WGS-84): 60 degrees 50 minutes N.
Longitude(WGS-84): 11 degrees 19 minutes E.
Finnish grid co-ordinates, Yhtenaiskoordinaatit:
Pohjoiskoordinaatti: 6849000, Itakoordinaatti: 2652000
The co-ordinates may include an error of up to 7 km The fire was detected in a satellite image acquired on 2012-04-30 at 17:42 UTC

Best regards

FF-OPERAT fire detection system,
at 2012-04-30 20:55 Finnish time

Please check and report:
___ The fire was a real forest fire
Area burned, if known: ________
We got the first information on the fire at: ________

___ The fire was a prescribed burning
Area burned, if known: ________

___ The fire was other fire, what type ? ____________________

___ The fire was NOT real

Would you please verify the fire and reply (by e-mail):

metsapalo@fmi.fi

Thank You

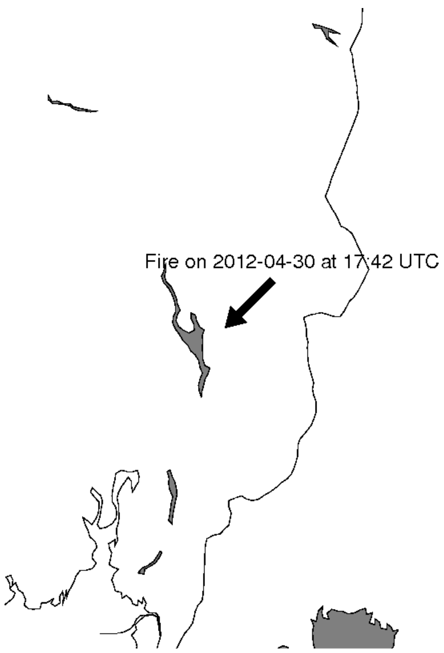

Figure 4: Top: A typical typical email message for a detected forest fire as submitted by the VTT/FMI fire detection system. The link in the message provides the picture on the bottom with an arrow pointing to the approximate location of the fire. This forest fire was detected close to the Swedish/Norwegian border.

- **Orbital delay:** The time from one orbit to the subsequent overpass.
- **Processing delay:** The time from the beginning of the satellite-overpass until the algorithm output.
- **Distribution delay:** The time from the fire detection until the local fire authorities receive the alert message.

While the first two factors for possible delays of the detection depend on the local conditions and are beyond the influence of the detection system, the later factors can be subject for possible improvements.

4.2 Status of the system

The forest fire detection operated by VTT and FMI has been used in 1993 and from 1994 on,. Together with the messaging system they have been operated during every forest fire season. The forest fire season is usually between spring and late summer. Since 2003, a current map with detected forest fires is regularly updated after every satellite overpass. The alert-service via email is operated since 2003. The time between the detection of a fire and the sending of the email usually is below 25 minutes.

Even if the service is used and operated for more than 18 years, the system is still considered as experimental. The system is successful and working stable. The success and the necessarity for such a service lead to an established system. However, the experimental state means that the forest fire detection to a certain degree depends on yearly decisions by the responsible authorities and also by the operating organisations FMI and VTT.

In Fig.5 all detected fires are shown. This figure provides an overview of the region covered by VTTs fire detection and supports the functionality of the system

4.3 Technical equipment and costs

Satellite receivers: The system for both, MODIS and AVHRR, uses to a large extend the satellite data infrastructure at FMI. The satellite data are routinely received from the overpassing satellites and used for weather services.

Computational requirements: The algorithms are based on computational inexpensive numerical filters. VTT uses FMI facilities to run the algorithms, together with the MODIS forest fire detection operated by FMI.

Storage requirements: The algorithm scans incoming satellite scenes. Scenes which do not contain detected forest fires are discarded.

Messaging: The email messaging system is automatic and sends a mail with the message to the regional dispatching center which is responsible for the located fire spot.

Maintenance: Even if the system is automated, a certain amount of maintenance is required for operating the system and analysing the performance. According to VTT and FMI the effort for maintenance is in the range of up to one man-month per year at each of the institutions, respectively.

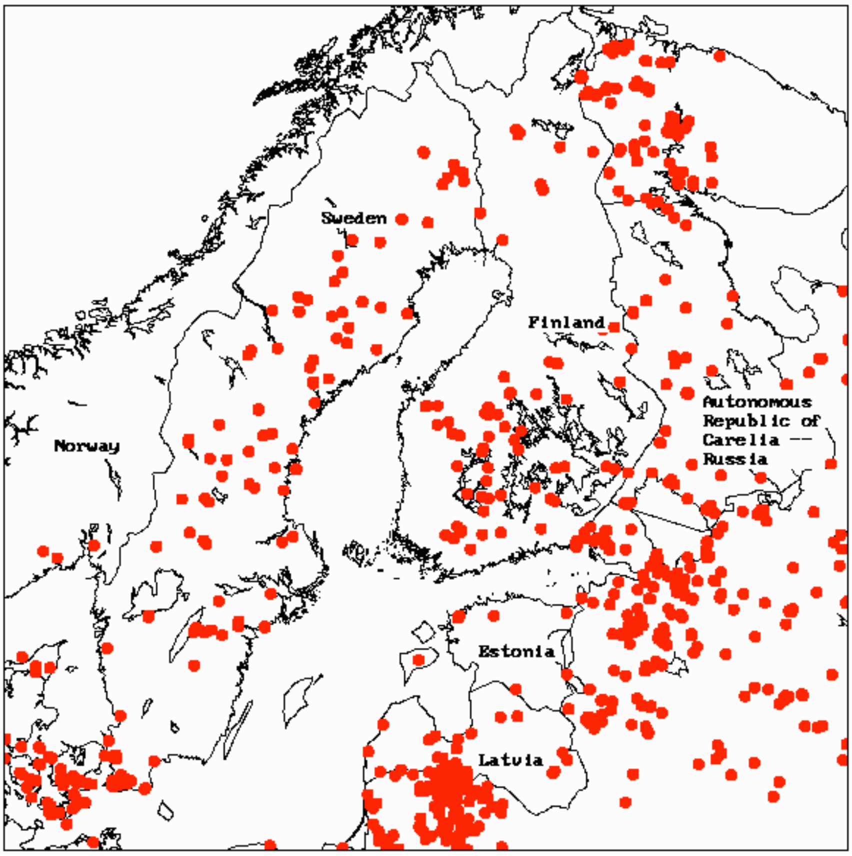

Figure 5: Detected fires for the period May 5 top September 15 1997. During this period, 1013 potential fires (hot spots) had been detected. To all fires in cooperating countries, email alerts had been sent. (Source: *http://virtual.vtt.fi/virtual/space/firealert/*)

4.4 Cooperation with Sweden

Currently MSB in Sweden gets an email in case that the system detects fire on Swedish territory or near the borders. Currently no operational distribution of this information/warning to Swedish regional centers or alarm centers exists. The FMI/VTT forest fire alerts are available for more than 15 years and the system is established, considering the fact that it is still considered experimental.

The continuation of the collaboration with VTT/FMI would have the advantage of low costs as no development costs for the system is to be expected. The development of a suitable distribution system from MSB to the regional dispatchment centers and fire authorities should be developed. This is necessary to ensure information about possible forest fires within shortest possible times.

One disadvantage with the use of VTT's forest fire alert system is the dependency on a service which is, due to its status as experimental, still depending on decisions of the Finnish authorities which decide from year to year. As VTT covers most of the countries around the Baltic Sea with the forest fire detection system, here an increased collaboration between Sweden/Finland and other countries could help to strengthen this service and establish it.

5 Use and availability of satellite data in Sweden

In Sweden, there is currently no independent system for the use of satellite-borne measurements of forest fires available.

The Swedish Forest Agency (Skogsstyrelsen) uses satellite data for mapping of changes in the forest structure and health as well as for observations of the current state of the forest. The satellite data, mainly SPOT data, are obtained from the providing agency on a yearly basis and changes in the satellite data from year to year are used to obtain information on long term changes, for forest mapping and inventory. There have been studies on the surveillance of forest areas and damages and changes related to forest fires. These studies are usually done after the forest fire season to asses the changes in forest coverage and in consequence the environmental and economical damages.

5.1 Swedish hydrological and meteorological institute (SMHI)

The Swedish weather service SMHI operates, as FMI, permanent satellite receiving facilities to obtain satellite data direct from overpassing satellites. As FMI, SMHI obtains data from the operational satellites of the NOAA and MetOp series as well as from the NASA EOS satellites Aqua and Terra and from the SUOMI satellite.

The data from AVHRR, MODIS and VIIRS/SUOMI are directly received and processed in the SMHI processing facilities. Currently, the incoming satellite data are used for the detection and classification of clouds. This information is important for meteorological analysis, short term weather forecasts and extreme weather warnings. The satellite data are processed operationally on a dedicated server system to provide the required cloud data as soon as possible. The cloud detection works on similar principles as the described forest fire detection. The measured signal in different channels for each pixel is processed by an algorithm using various test with respect to thresholds and gradient to determine cloud properties and cloud type.

5.2 Development of a forest fire warning at SMHI

SMHI has experience with the storage and processing of data from operational polar orbiting satellite including the required infrastructure to realise the processing. SMHI has an active research group working on processing of satellite data, which is continuously developing and improving algorithms. They are also running and maintaining the operational processing chains for cloud detection.

The above described method or algorithm to detect signals of active forest fires in AVHRR and MODIS measurements is very closely related to algorithms used for the detection of cloud parameters.

The procedure for the fire detection and the principles of the algorithms are well described in literature as e.g. in *Li et al.* (2000); *Kaufman et al.* (1990); *Rauste et al.* (1997). According to VTT the computational power for the AVHRR fire product is a minor issue as the algorithm is straight forward and does not require large memory. It has been operated for more than 15 years. Storage should be a minor problem. Following the principle by VTT, only scenes with detected fires are stored.

With this information in mind, the discussion with SMHI (*Scheirer and Dybbroe, personal communication, 2012*) indicated that it should be possible to develop and include algorithms as described for AVHRR and MODIS forest fire detection in the SMHI satellite data processing chain. As MODIS, AVHRR and soon VIIRS are operationally processed, a forest-fire product could be included as a "by-product" for the calculated cloud masks. The development and implementation of such a forest-fire warning can probably realised within a comparatively short time. Based on their experience and on the principle of the detection, a prototype of the detection system can be available within a few weeks. However, there are some more steps to take until a fully operational system is available. Considering the implementation in to the existing processing chain, thorough testing, validation and adaption of parameters, the estimate is that a running algorithm can be available after approx. 6 months.

The implementation in the system can be done in different steps, depending of the state of the development and the satellite processing system. The satellite research group has a development server on which the algorithms are developed and tested. The algorithm can then be operated on one of the test-servers within an active environment. Here the system runs under real conditions in parallel to the operational processing without the risk of interfering with the operational processing in case of upcoming problems. If the forest fire detection cannot become a part of the operational system, it is still possible to operate it on the test server system to avoid conflicts with the operational system.

The establishment of an operational forest fire detection in Sweden is possible with reasonable efforts. The basic technical issues are identified and solvable. However, there are some aspects which have to be considered:

- For the cloud detection no mask with information of industrial sites is required. A mask providing this information together with other surface properties should be implemented.

- The cloud-products are published to a different user community. A distribution channel for the fire-products needs to be established. Here a messaging system sending a message to MSB for further distribution could be a possible solution. The costs for similar services from SMHI are in the range of up to 1000 SEk per month.(*Helen Ivars, SMHI, personal communication*).
- Currently no distribution network for the regional dispatchment centers and alarm centers in Sweden exists. Here a solution has to be developed.

5.3 Synergies

SMHI already provides MSB with other information related to the hydrological and meteorological parameters which determine the risk of forest fires. Here the inclusion of the forest fire detection and possible other satellite data related to the estimation of the risk of forest fires can complement the information basis and improve the awareness during the forest fire season.

The partly satellite-borne inventory of the forests made by the Swedish forest agency could be used to classify forest regions according to their vegetation structure. Depending on the mixture of surface vegetation, surface properties and types of bushes and trees in the forests, different resources with respect to available fuel can determine the fire risk and intensity. Here inventory data by the forest agency in combination with fire risk analysis from SMHI can help to assess the real risk for forest fires and also the expected severity of fires in certain areas.

There are several indices which can be determined with satellite images. Such indices are based on the differences in change of properties in different spectral regions with changing surface properties. E.g. does the reflectivity in the VIS range change in a different way than the radiation in the near IR if the canopy layer of the vegetation is affected by drought. Different combination and weighting on various channels can provide varying information on the state, dryness, and healthiness of the vegetation.

5.3.1 Normalized Multi-band Drought Index (NMDI)

The NMDI is an indexed based on different bands in the MODIS suite and relates a channel which is insensitive to leaf water content to the difference between two channels which are sensitive to soil and vegetation water. This index provides an estimate on the dryness of the soil and the vegetation and thus an assessment of the fire conditions (*Wang et al.*, 2008). Additionally, this index also provides information about forest fires and can be used to support the detection. However, this index is not applicable to AVHRR data.

5.3.2 Normalized Difference Vegetation Index (NDVI)

The “Normalized Difference Vegetation Index” provides information on the vegetation cover of a pixel. The ratio between the difference of measurements in the NIR (around 1μm) and in the VIS and the sum of both channels. The index reflects the strong difference in reflectivity for healthy vegetation in both spectral ranges. The index can provide information on the vegetation cover and, to a certain extent, on the healthiness of the vegetation in observed areas. This information can support the assessment for fire risk in certain areas.

6 Conclusions and outlook

The methods for satellite borne detection of forest fires provide useful tools which can support early fire recognition in forest areas. Especially in Sweden, and Scandinavia in general, the large forests with partly very low population, satellite borne fire detection can help to detect hot spots in remote places early enough to initiate the required activities.

The use of observations from operational meteorological satellites has several advantages. Weather services in most countries, including Sweden and Finland have direct access to the data. The measurements are directly retrieved from the satellite during its overpass and can be processed immediately. The availability of data from up to 10 satellites provides a large set of redundant measurements. The temporal distribution of the satellite overpasses allow the detection of forest fires and hot spots during most times of the day. Under clear sky conditions, a forest fire of the detectable size can be observed within a few hours, even at remote places.

Several countries and institutions use channels around the 3.7 μm region for the detection of hot spots. This spectral region is very sensitive to the typical temperature ranges expected for forest fires. Since this channel is affected by reflected sunlight and warm surfaces, heated by sunlight, channels in the visible and thermal infrared are used to exclude cases where no fire is present.

In Finland VTT and FMI operate a forest fire detection system using the directly retrieved data from VIS/IR radiometers on board European and US operational weather satellites and som additional scientific satellites. The forest fire detection is operational since 1994 and provides good results during the forest fire seasons for fires large enough to be detectable by the senors. The amount of erroneously detected fires is in the range of 12 to 16 %, based on the feedback that is sent back to VTT/FMI by the affected authorities.

The system is well established and the area observed by the system covers, beside Finland, Sweden, Norway, parts of Russia and most countries around the East Baltic Sea. The email messaging system, which distributes information on detected fires to the regional dispatching centers, sends messages to authorities in the neighboring countries. Among these countries MSB in Sweden receives emails on detected hot spots on Swedish ground or close to the borders. Currently there is no automated further distribution for such messages available.

The cooperation between Finland and Sweden is currently not very well established. Even if email messages for detected fires are sent to Swedish authorities, this information is not further distributed. Additionally, the fact that the VTT/FMI fire detection system is still considered to be experimental, makes future planning for a Swedish forest fire notification network on basis of the FMI/VTT system uncertain. A reliable solution on basis of this system requires a reliable status as operational system in Finland. Furthermore, a operational network for automatic distribution of the forest fire notifications should be established to minimize the risk of lost notifications. A solution based on the FMI/VTT system could be possible if all countries, which are already covered by the Finnish fire detection network contribute to build up a functional joint network. However, this requires certain efforts on international levels.

On the other hand, Sweden already has an infrastructure which supports the development of its own fire detection system, similar to the one operated by VTT/FMI, within reasonable time. At SMHI, satellite data from all operational polar orbiting satellites with the detectors, which are used for the detection of fires, are received. The satellite data section at SMHI operates various programs used for the operational weather forecasts, among others algorithms for cloud classification and detection. The basic principle for the cloud algorithms is similar to the ones for the fire detection system. With the experience at SMHI, the development and implementation of a fire detection system can be realised in comparatively short time and implemented in an operational system. A fire detection system in Sweden on collaboration with SMHI and other affected authorities would provide autonomy from other countries and authorities and could be operational within several months.

6.1 Outlook - minor projects

The discussion with SMHI and MSB lead to some fruitful ideas for further work on this project. These are minor studies which could be seen to prepare the development of the fire detection system or, to improve the detection system especially with respect to its application for Scandinavian conditions.

6.1.1 Master-thesis - development of a forest fire detection prototype

Independent of the future plans for a forest fire detection, a MSc-thesis for students who are interested in remote sensing and data evaluation is a possibility to initiate the work on this subject in collaboration with SMHI and MSB. The algorithms for forest fire detection are well described and provide a good basis for a student project. As this is not intended for operational use, different issues related to forest fire detection can be assessed and evaluated with a certain freedom. Here especially the special conditions in Sweden and Northern Europe with respect to vegetation, forest-cover and observation conditions can be considered in more detail.

6.1.2 Study on forest fire detection under certain weather regimes

In the case that a semi-operational or operational forest fire detection would be developed, this could be a good basis for further studies on the forest fire detection. The fact that the forest fire detection can be developed in close collaboration with the observation of meteorological parameters and cloud properties, using the same satellite data, provides a good basis for studies of the influence of certain weather conditions on the detectability. Here, especially the sensitivity to interfering clouds in the infrared range can be evaluated. E.g. studies on the perfomance of the forest fire detection under certain conditions of clouds, mainly thin cirrus clouds or scattered clouds could help to improve the forest fire detection or define the boundary conditions of satellite borne forest fire detection more clearly.

References

Hansen, R. (2003), *Skogsbrandsläckning*, Räddningsverket, ISBN 91-7253-171-1.

Kaufman, Y. J., C. J. Tucker, and I. Fung (1990), Remote sensingof biomass burning in the tropics, *J. Geophys. Res.*, *95*(D7), 9927–9939.

Kelhä, V., Y. Rauste, T. Häme, T. Sephton, O. Frauenberger, K. Soini, A. Venäläinen, J. S. Miguel-Ayanz, and T. Vainio (2001), Promotion of space technologies for supporting the management of natural disasters: Earth observation technologies for decision support "fire risk management in finland", *Tech. rep.*, Final Report, ESA, Contract No. 13727/99/I-DC.

Kelhä, V., et al. (2003), Combining avhrr and atsr satellite sensor data for operational boreal forest fire detection, doi:10.1080/01431160210144705.

Li, Z., S. Nadon, and J. Cihlar (2000), Satellite-based detection of canadian boreal forest fires: development and application of the algorithm, *Int. J. Remote Sensing*, *21*(16), 30573069.

Matson, M., and J. Dozier (1981), Identification of subresolution high temperature sources using a thermal ir sensor, *Photogrammetric Engineering and Remote Sensing*, *47*(9), 1311–1318.

Matson, M., G. Stephens, and J. Robinson (1987), Fire detection using data from the NOAA-n satellites, *Int. J. Remote Sensing*, *8*(7), 961–970.

Rauste, Y., E. Herland, , H. Frelander, K. Soini, T. Kuoremaki, and A. Roukari (1997), Satellite-based forest fire detection for fire control in boreal forests, *Int. J. Remote Sensing*, *18*(12), 2641–2656, doi:10.1080/014311697217512.

Wang, L., J. J. Qu, and X. Hao (2008), Forest fire detection using the normalized multi-band drought index (NMDI) with satellite measurements, *Agricultural and Forest Meteorology*, *148*(11), 1767 – 1776.

A Satellite overpass times for other satellites

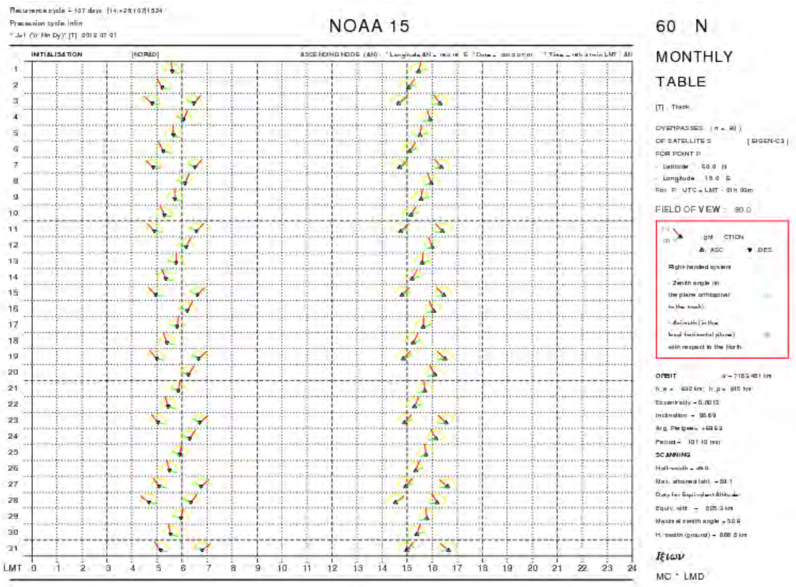

Figure 6: As Fig. 2 but for NOAA15.

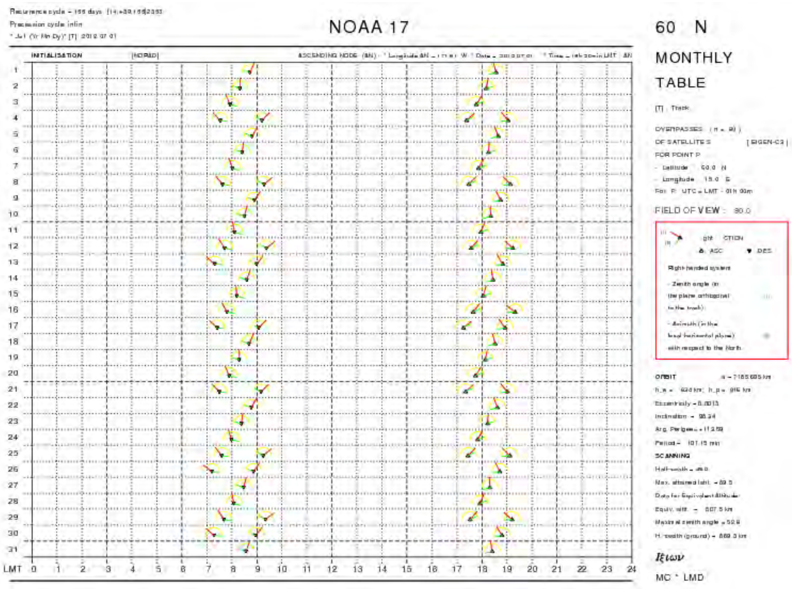

Figure 7: As Fig. 2 but for NOAA17.

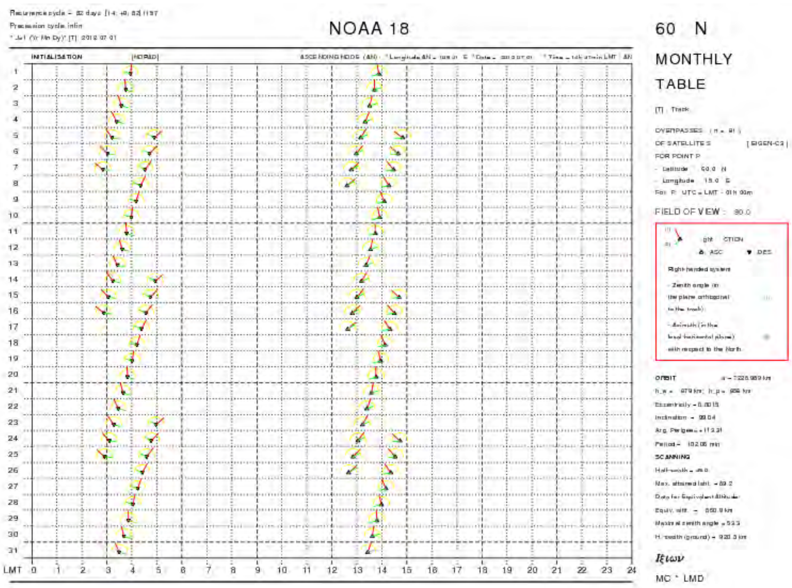

Figure 8: As Fig. 2 but for NOAA18.

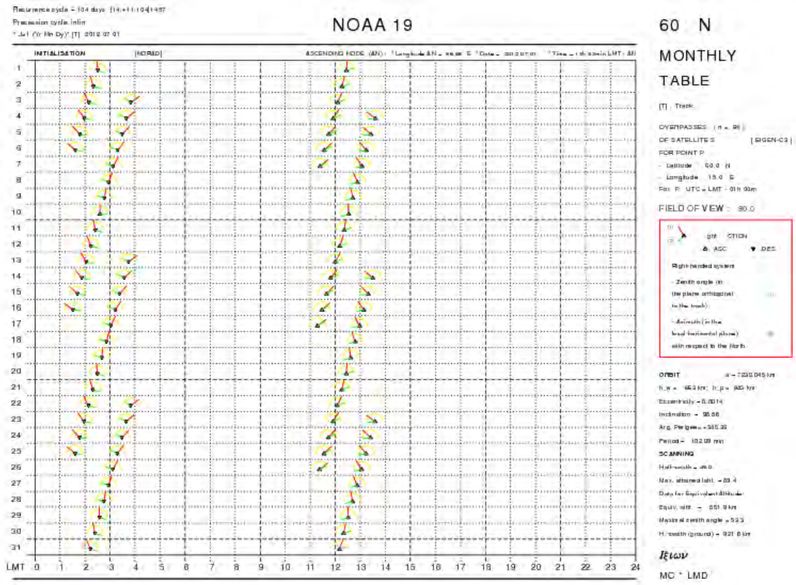

Figure 9: As Fig. 2 but for NOAA19.

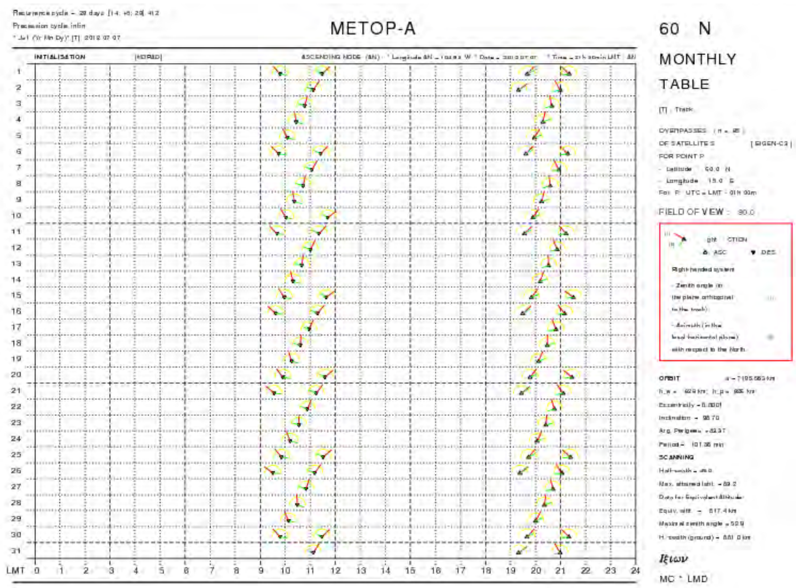

Figure 10: As Fig. 2 but for MetOp-A.

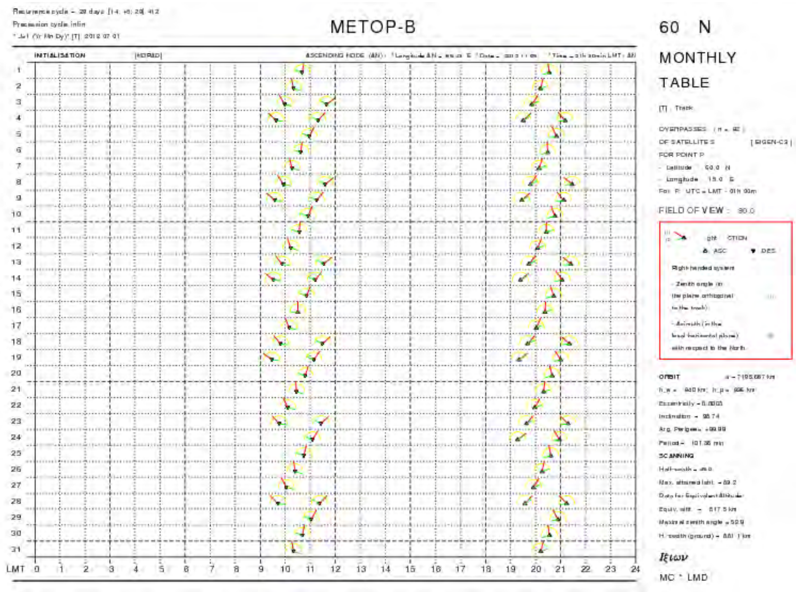

Figure 11: As Fig. 2 but for MetOp-B.

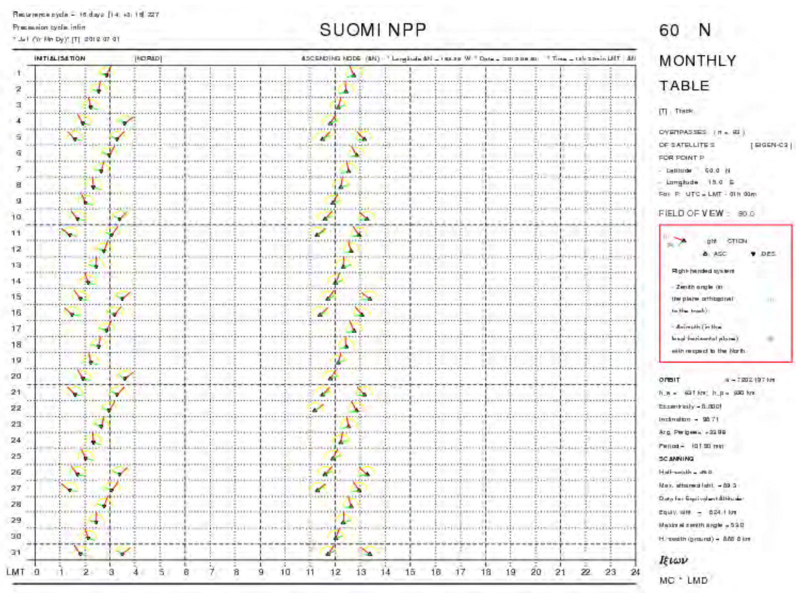

Figure 12: As Fig. 2 but for SUOMI.