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Weather satellites

FORECASTING THE WEATHER

The arrival of the telegraph in North America in the mid 1800s led to the invention of weather forecasting as we know it. Not the “red sky at night shepherd’s or sailor’s delight” type of forecast, but a recognition that weather conditions are transferred from one place to the next by the winds. Cleveland Abbe is usually cited as the first modern weather observer, initiating a network of weather stations linked by telegraph in 1869. The success of this initiative led to the creation of the national weather service in 1870. Run by the US Army Signal Corps, Cleveland Abbe was appointed its chief scientist.

Today, satellites show us that the weather on the far side of the world affects our weather in 4 or 5 days’ time. Sequences of pictures from satellites high above North America and the Atlantic Ocean show cloud formations forming in the Pacific Ocean and traveling all the way across Canada before eventually reaching Europe. This sequence doesn’t happen all of the time – that would make forecasting too easy – but it does happen sufficiently often to demonstrate the linkage in a general sense of Europe’s weather today to that in the Pacific Ocean off America’s West Coast several days before.

This inter-continental linkage of weather systems was recognized during World War II when it was realized that the so-called “fire-balloons” landing in the USA and Canada had traveled in about 3 days all the way across the Pacific Ocean from Japan. The balloons were carried along at above 30,000 ft (9 km) by what we now call the Jet Stream.

Before the age of satellites, weather bureaux collected data from weather stations and ships, buoys and balloons – the balloons carried weather instruments such as a thermometer and barometer and a radio to send the data collected as they rose through the atmosphere back to the ground. The data tended to come from wealthy nations, to be very sparse over the oceans and poor countries, and to be particularly sparse in the southern hemisphere and in both polar regions. Satellites have made the

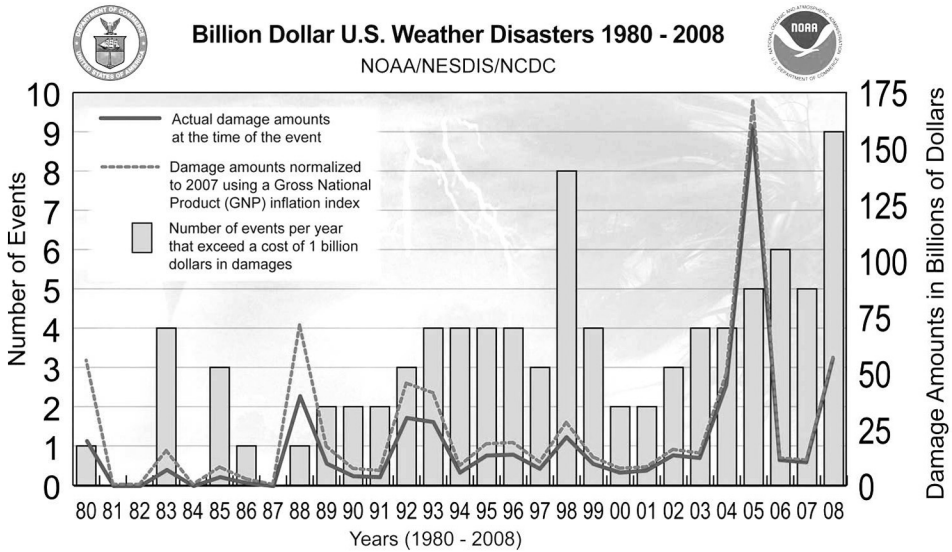


Figure 8. Economic losses caused by US weather disasters. Credit: NOAA/NESDIS/NCDC.

location of the data more democratic – satellites don’t distinguish between rich and poor countries, or between land and sea. Satellites spot the clouds – at least the tops of the clouds – and can measure sea state (the height and direction of waves), sea surface temperature, wind speed and direction, humidity and some of the chemical constituents of the air such as ozone. Some of these satellite measurements can only be made under clear skies and in daytime, but many are possible whatever the weather or the time of day.

Satellites suffer from the fact that they are hundreds, or in some cases thousands, of miles above the earth. Being on the spot with your thermometer, your wind vane, your humidity reader, your barometer and so on is likely to provide more accurate measurements than those taken by a distant satellite. And satellites are expensive – the costs range from tens of millions of dollars to a billion or more in the case of the most sophisticated satellites. But ships are expensive – millions of dollars – and you would need tens of thousands of them to cover all the oceans. So weather forecasters have come to realize that satellites are the cost-effective option, the way to get the best bang for your buck. As a consequence, the British Met Office says that over 70% of the data they use in their most accurate weather forecasts come from satellites – and the proportion is growing.

The money is deemed well spent. Dr Jack Hayes, a top official in the US weather agency, claims that a third of the US economy is sensitive to weather and climate (see Figure 8). He goes on to list the results of bad weather, including 7,400 deaths and 600,000 injuries each year and two-thirds of air traffic delays. He reckons

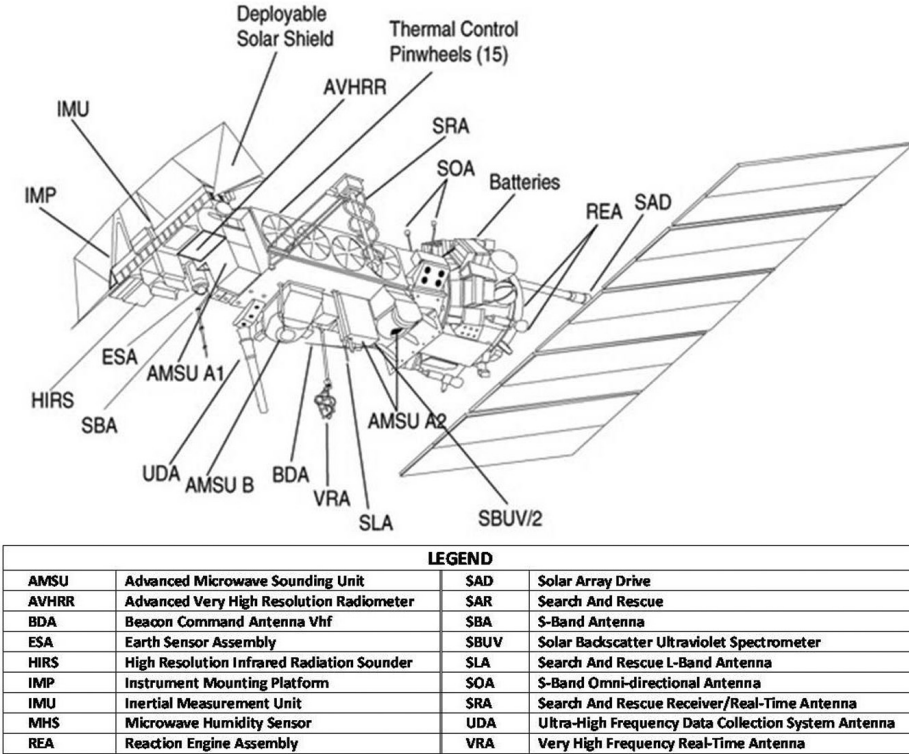


Figure 9. Schematic diagram of the current US low-orbit weather satellite. Credit: NOAA.

that improved forecasts offer a saving of \$18 billion in the air transport sector alone.¹ A year earlier, he stated that much of the improvement in recent weather forecasts was due to weather satellites. “A three day forecast with satellites is as good as a one day forecast without satellites,” he claimed. His National Oceanic & Atmospheric Administration (NOAA) colleague, Mary Glackin, told a House of Representatives Subcommittee in June 2009 that NOAA could not produce useful 4 and 5-day hurricane track forecasts if there was a gap in satellite coverage of 6 months.²

The drawing of a modern weather satellite in Figure 9 suggests how complex they are. Costing \$564 to build and launch, the NOAA-19 satellite was in the news long before it reached the launch site. The two most prominent features in the drawing are the solar panel on the right and the sunshade (called “solar shield” in the drawing) on the left. The 6-m (20-ft)-long solar panel is covered with solar cells on the side facing the sun and provides more than 800 W of electrical power. The sunshade protects the cameras from direct sunlight much as you might shade the lens of your

¹ Hayes (2009).

² Hayes (2008), and Canan (2009).

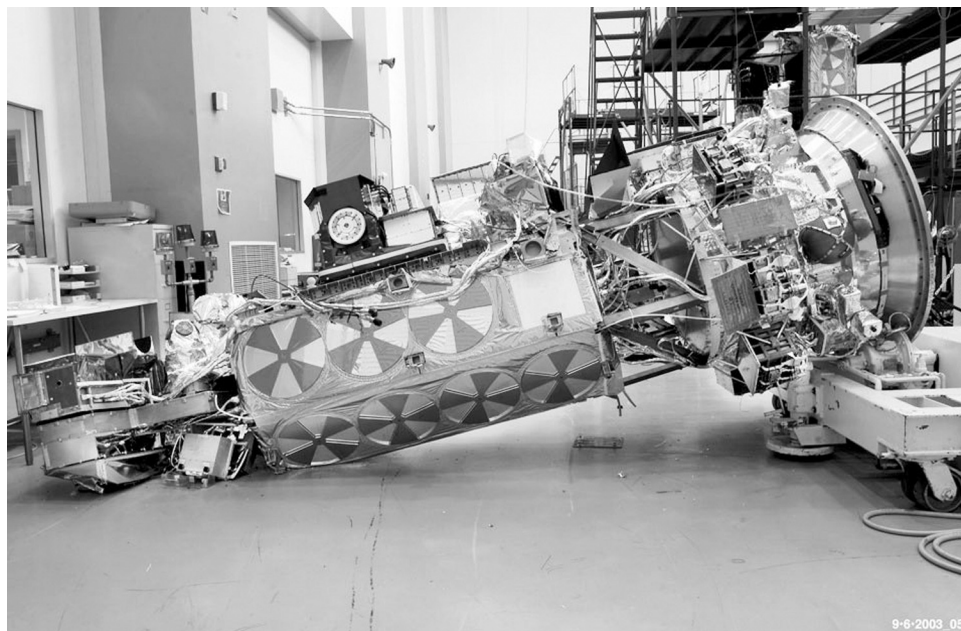


Figure 10. NOAA N-Prime (later NOAA-19) on the floor at Lockheed Martin’s factory in Silicon Valley, California. Credit: NASA.

camera with the flat of your hand when taking photos in the sun. The cameras and other instruments themselves are relatively inconspicuous. The main camera is the AVHRR, which is located under the sunshade on the left. The other instruments that measure the temperature, humidity and constituents of the atmosphere are placed along the underside of the 4¼-m (14-ft)-long body. The right-hand end of the satellite contains batteries, small rocket motors to control the orbit and pointing direction, fuel tanks and other “housekeeping” items. The overall weight of the satellite including $\frac{3}{4}$ ton of fuel is $2\frac{1}{4}$ tons.

NOAA-19 made the news in 2003 for reasons illustrated in Figure 10. Following a change of shift, the Lockheed Martin team that was building the satellite started to lower it from the vertical to the horizontal so that they could gain access to the Microwave Humidity Sounder. The previous shift hadn’t inserted the 24 bolts that held the satellite to the gantry, assuming the next shift would, and vice versa – and the paperwork signed off at start and end of shifts suggested that the bolts were in place. Newton’s laws of gravity apply in Silicon Valley just like everywhere else and the 1-ton satellite smashed to the floor, thankfully without injuring anyone.

Nearly 6 years and \$250 million later, NOAA-19 had been repaired and was ready to be launched, as illustrated in Figure 11. This figure gives a good impression of the size of the satellite compared with the engineers at its base. The bolts on this occasion have been put in place to prevent it falling as it is raised from the horizontal to the vertical. Eventually, it was successfully placed in orbit on February 6th 2009.

Table 1 lists all current low-orbiting operational weather satellites. There are, in

Table 1. Low-orbit weather satellites as of July 2010
(satellites to be launched in 2010 in italics).

<i>Country</i>	<i>Satellites (launch dates)</i>	<i>Parameters measured</i>
USA	NOAA-15 (1998), NOAA-16 (2000), NOAA-18 (2005), NOAA-19 (2009), DMSP-F14* (1997), DMSP-F15 (1999), DMSP-F16 (2003), DMSP-F17 (2006), DMSP-F18 (2009)	Multi-spectral low-resolution imaging, atmospheric temperature and moisture content, stratospheric ozone, aerosols
Europe	Metop-1 (2006)	Similar to USA plus surface winds
China	FY-1D (2002), FY-3A (2008), <i>FY-3B (2010)</i>	Similar to USA plus ocean color imager
Russia	Meteor M-N1 (2009), <i>Meteor M-N2 (2010)</i>	Prototype – similar to USA plus low-resolution imaging radar for ice monitoring

addition, more than 30 satellites whose data assist weather researchers to understand the subject better but are not routinely used in weather forecasting.³

Many countries have weather-forecasting bureaux and you might wonder at the economics of having separate (and separately funded) forecasters in neighboring small countries. Fortunately, this fragmentation has been mainly avoided when it comes to weather satellites. Through the World Meteorological Organisation (an agency of the UN), countries have agreed to share their weather satellite data with each other. They have also divided up responsibility for providing weather satellites at an altitude of 36,000 km around the equator – the altitude at which the satellite is moving at the same speed as the earth is rotating below, thus appearing stationary in the sky above the equator (the satellite is said to be in a “geostationary” orbit). A geostationary satellite is so high in the sky that it can see almost all the way to the poles – the image becomes foreshortened and thus hard to interpret the further away from the equator you go, but data out to 50° latitude is fine, which covers most of the inhabited areas of the globe. The USA has committed to providing two such satellites: GOES West, covering the eastern Pacific from beyond Hawaii to the central part of North America, and GOES East, covering from there to the eastern Atlantic near Africa;⁴ Europe (through the Eumetsat organization), China, India, Japan, Korea and Russia also provide similar satellites, as listed in Table 2.

Besides the geostationary satellites 36,000 km out in space, the USA, Europe, China and Russia also provide weather satellites that are at an altitude of about 850 km (see Table 1). These have the advantage of being a lot closer to the weather

³ CGMS (2010) pp. 26–28.

⁴ Davis (2007).

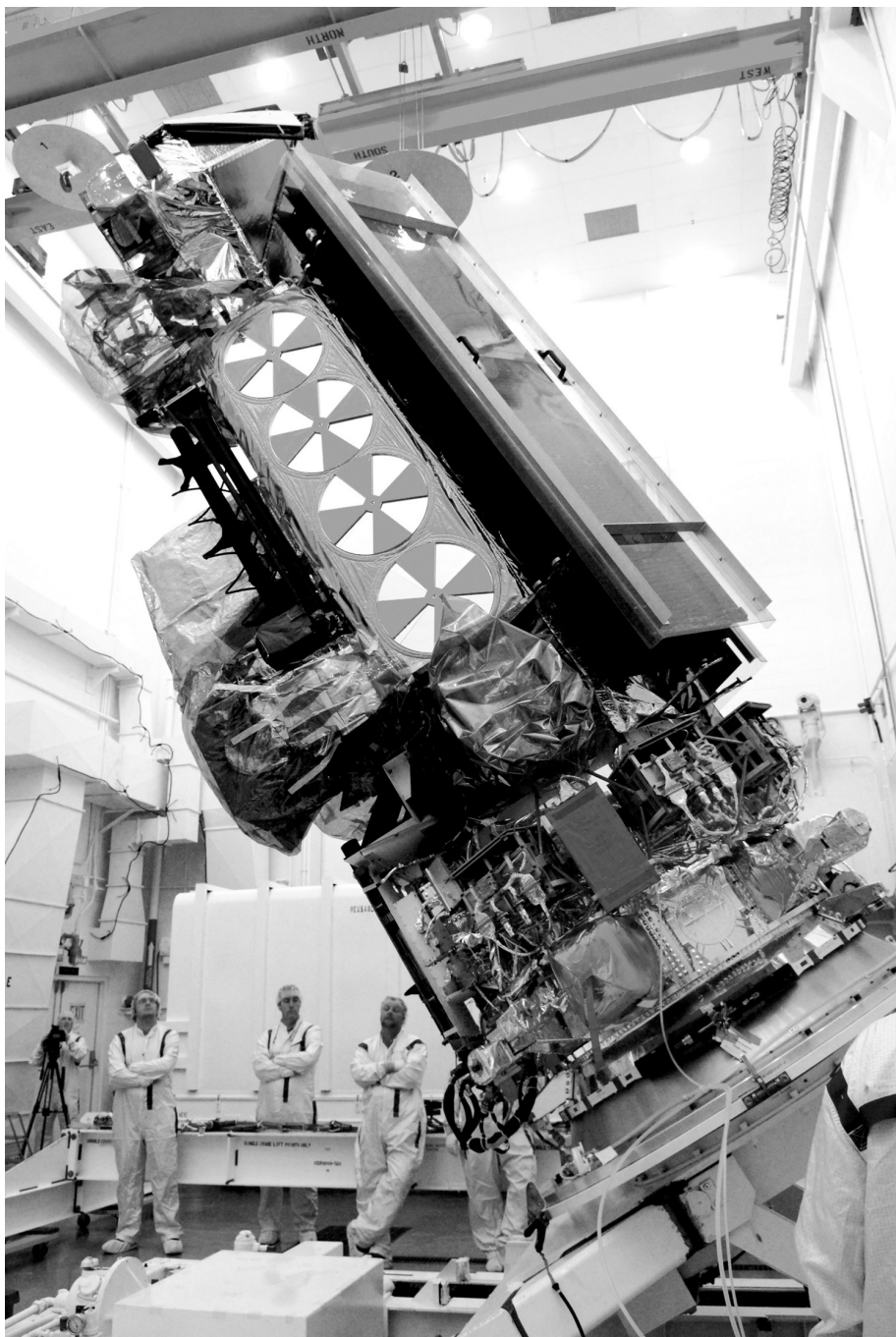


Figure 11. NOAA-19 being prepared for launch at Vandenberg Air Force Base, California. Credit: NASA/NOAA.

Table 2. Geostationary weather satellites as of July 2010 (satellites to be launched in 2010 in italics).⁵

<i>Country</i>	<i>Longitude</i>	<i>Name</i>	<i>Launched</i>	<i>Channels</i>	<i>Comments</i>
USA	135°W	GOES-11	2000	5	Operational: West
	75°W	GOES-13	2006	5	Operational: East
	105°W	GOES-15	2010	5	back-up
	89.5°W	GOES-14	2009	5	back-up
	60°W	GOES-12	2001	5	South America
Europe	0°	Meteosat-9 (MSG-2)	2005	12	E. Atlantic
	9.5°E	Meteosat-8 (MSG-1)	2002	12	Rapid scan service
	57.5°E	Meteosat-7	1997	3	W. Indian Ocean
	67.5°E	Meteosat-6	1993	3	Back-up
India	74°E	Kalpana-1 (METSAT)	2002	3	
<i>Russia</i>	<i>76°E</i>	<i>Electro-L N1</i>	<i>2010</i>	<i>10</i>	<i>Planned</i>
<i>India</i>	<i>82°E</i>	<i>INSAT-3D</i>	<i>2010</i>	<i>6</i>	<i>Planned</i>
China	86.5E	FY-2D	2006	5	
India	93.5°E	Insat-3A	2003	3	
China	123.5°E	FY-2C	2004	5	Back-up
S Korea	128.2°E	COMS-1	2010	5	
China	105°E	FY-2E	2008	5	
Japan	140°E	Himawari-6 (MTSAT-1R)	2005	5	
	145°E	Himawari-7 (MTSAT-2)	2006	5	Stand-by

than the geostationary (GEO) satellites and can get more detail, but they only see each region of the globe for a few minutes before their trajectory takes them over the horizon. These Low Earth Orbiting (LEO) satellites typically see each part of the globe twice a day, so a combination of LEO and GEO weather satellites gives a combination of data that is continuous but less detailed, and occasional but more detailed.

The five countries that originally agreed to provide geostationary weather satellites (USA, Europe, Russia, China and Japan) have now been joined by India's Insat series and South Korea's COMS-1 satellite. You might wonder why South Korea needs to launch a geostationary weather satellite, since its close neighbors China and Japan already do so. Lee Joo-jin, who is the head of South Korea's space agency, KARI, says "The problem with our meteorological system now is that we rely on information provided by Japanese satellites, which provide information

⁵ WMO (2010).

updates every 30 minutes. COMS-1 will reduce this gap to 8 to 10 minutes, which will dramatically improve the accuracy of weather reports and put the country in a better position to prevent damage from natural disasters".⁶ The cost of over \$300 million seems high for the reduced time delay, and the camera and satellite are being bought from the USA and Europe, respectively, so local industry is not benefitting directly. We can be forgiven for surmising that the unstated reason for COMS-1 being deployed is that being dependent on China and (especially) Japan has sometimes been an unpleasant experience for South Korea in the past.

The first weather satellite was the Tiros satellite, launched in 1960, and some of its features remain unchanged in its successors today. The Tiros camera used TV-type cathode ray tube technology, which today is replaced by the sort of digital technology you have in your cell phone or digital camera. The images showed very little detail and that is still the case today, when the smallest features visible in weather images are typically 1 km or more in size. The lack of detail saves on the bandwidth to transmit the images to the ground – just as you pay more the better your broadband internet connection is. Weather satellites broadcast their images to the ground in two formats. One is a format that can be received by cheap and cheerful terminals. Originally, the format was that of the facsimile or fax, which, in recent years, has been replaced by a digital equivalent. The idea is that small organizations and individuals can afford to own a weather satellite terminal.

The second format contains more detail and is that used by the main weather forecasting agencies. Once received on the ground, it is processed to remove defects and to extract weather information. For example, consecutive geostationary images are processed by computer so that the movement of individual clouds can show the wind speeds and direction – an animation of this process can be seen on the Eumetsat website.⁷ However, a small change in the camera or the satellite between or during images might be interpreted as a cloud movement, so, first, the computer checks each image by identifying landmarks and distorting the image so that the landmarks are all in their proper places. Then, the computer uses the shape of the clouds to find how they have moved between successive images – typically 15 min or so apart. Finally, a separate infrared (heat-sensing) image of the same scene is consulted to determine the height of each cloud – the warmer the cloud, the lower its altitude. By this combination of geostationary weather satellite and sophisticated computer pattern recognition, weather forecasters get a snapshot of the winds around the globe every few hours.

Figure 12 shows a typical output of this process from the Meteosat satellite located above 0° longitude (directly above the center of the figure). Weather patterns at different levels are evident over land and ocean.⁸

⁶ Kim Tong-hyung (2010).

⁷ www.eumetsat.int/Home/Main/Access_to_Data/Meteosat_Meteorological_Products/Product_List/SP_1119537341561?l=en.

⁸ The computer system to extract wind and other weather information from Meteosat images was developed by the team I work with at Logica plc.

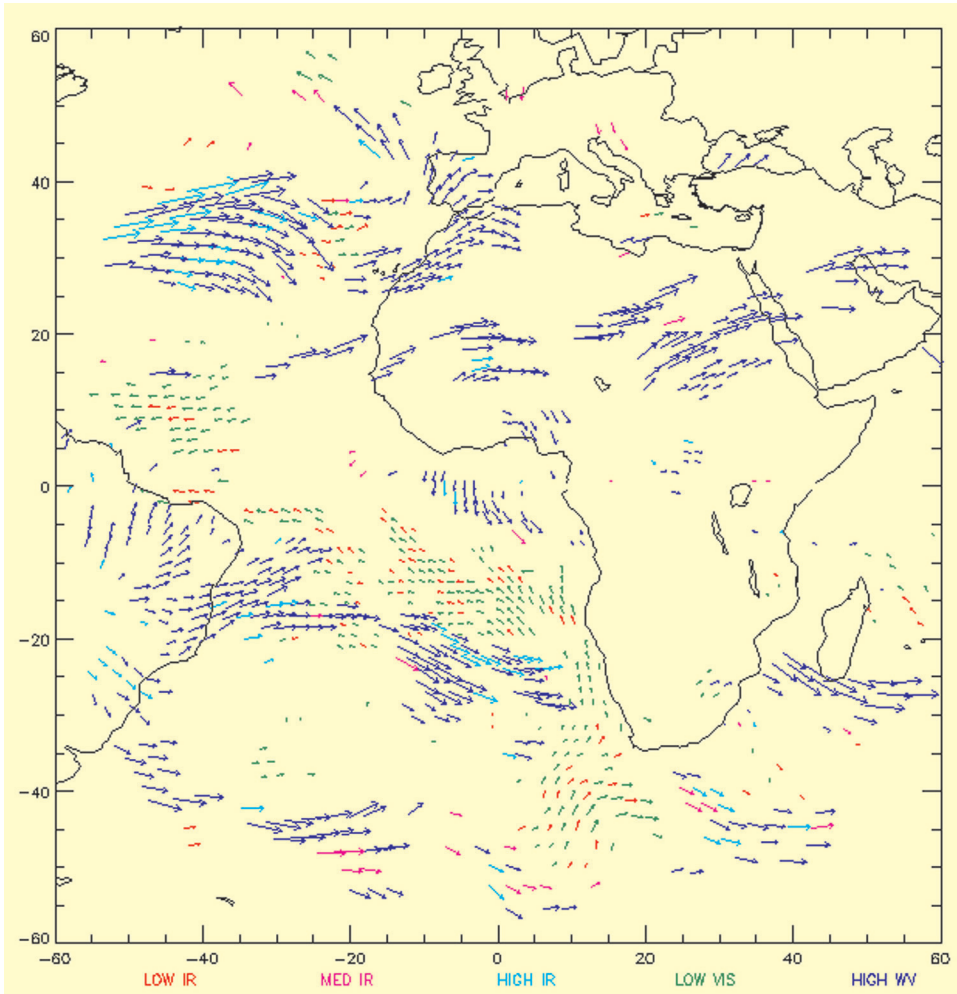


Figure 12. Wind directions (arrow) and speeds (length of arrow) at high (light and dark blue), medium (pink) and low (red and green) altitudes computed from three Meteosat images on April 16th 1997 using data from three channels: visible (green), infrared (red, pink and light blue) and water vapor (dark blue). Credit: Eumetsat.

The list of current geostationary weather satellites in Table 2 includes the number of “channels”. The equipment on each satellite takes several images at a time, each in a different color (effectively, each color has its own separate camera). Most of the colors are in the infrared in order to pick out features in the sea or cloud, so the word “color” isn’t really appropriate, since infrared is invisible to the human eye. The satellite people speak about bands or channels instead of colors. Europe’s two most recent satellites, Meteosat-8 and -9 (previously called MSG-1 and -2), take images in 12 channels, three of which are in the visible part of the spectrum. The other nine

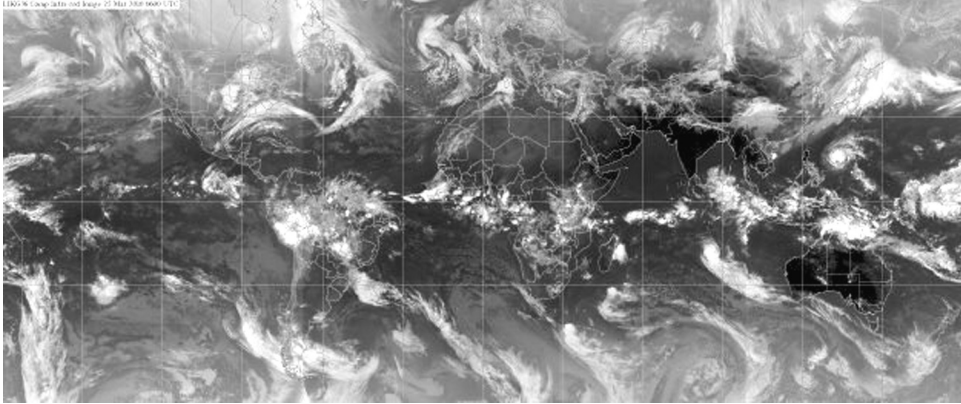


Figure 13. Composite of geostationary images on March 25th 2010 at 06:00 (GMT) with latitude–longitude lines and political boundaries added by computer.

channels are in the infrared, each chosen to detect clouds or humidity at a particular altitude – their use for detecting volcanic ash will be mentioned in the next chapter.

Figure 13 shows how imagery from several geostationary satellites can be spliced together to give a snapshot of the world’s weather. The image is in the infrared, where black means hot and white means cold. The time of this particular composite image is 06:00 GMT, so it’s early morning in the UK (the *Greenwich* in Greenwich Mean Time, GMT, is a suburb of London). Thus, India and Australia are experiencing the full heat of the day and appear black, whereas it is still nighttime in Europe and America. The whiter the clouds, the colder they are – and cold means high. The light-gray clouds are closer to the surface. Weather patterns stand out clearly, such as a frontal system over the south-east of the USA out into the Atlantic and a circular storm to the east of the Philippines.

In principle, images from a LEO satellite can also be used to spot cloud movements and thus wind speeds. At the equator, there will be many hours between LEO images, in which time the clouds have changed shape or disappeared. However, near the poles, these orbits tend to converge – the satellite orbits from pole to pole so that the earth has turned beneath it each time it gets back to the equator. So, a LEO satellite might get successive images of a polar region after about 90 min (the duration of a LEO orbit), which is fine for tracking individual clouds. As noted above, geostationary satellites give little or no information about the polar regions, hence the usefulness of the LEO data.

Another source of wind information is to measure the direction and height of waves on the sea surface. Several low-orbiting satellites carry instruments that measure this information, but Europe’s Metop-1 is currently the only operational weather satellite that does so.

Figure 14 illustrates how satellites pick out weather patterns that are smaller than continental scale but still too large to be seen as a whole by aircraft- or balloon-borne sensors. Taken by NASA’s Terra satellite on March 20th 2010, the lower half of this natural color image shows a sandstorm over eastern China that has swept in

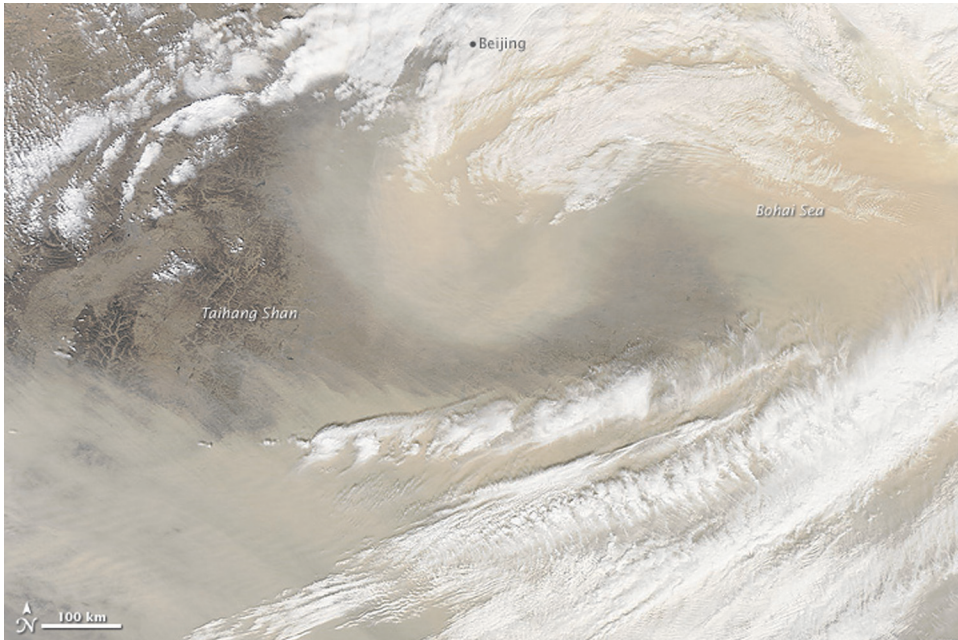


Figure 14. Sandstorm in China illustrating a “comma”-shaped wind pattern captured by the MODIS instrument on NASA’s Terra satellite (see text for explanation). The scale is shown in the lower left. Credit: NASA’s Earth Observatory.

from the dry dust plateaus to the north and west. NASA’s website⁹ explains that the sandstorm “wraps around the right-hand side in a comma shape that terminates in a large ball of dust near image center. This pattern is consistent with the passing of a cold weather front bearing a strong area of low pressure at the surface. These weather systems, known as mid-latitude cyclones, are often associated with giant comma-shaped clouds that reveal how air from a very wide area gets drawn in toward the low-pressure heart of the storm”. The sand degrades the air quality in China’s cities and obscures landmarks to the point at which we cannot see where the land ends and the sea to the right begins. Only the mountains to the lower left are recognizable – the NASA annotator has identified the Taihang Shang (mountains), which mark the easterly edge of the North China plateau.

American weather satellites are owned and operated by the National Oceanic and Atmospheric Administration (NOAA). It might seem odd that NASA doesn’t take care of them – after all, isn’t it NASA’s job to run non-military satellites for the government? NASA did develop the early weather satellites, but it soon became clear that NASA’s culture of seeking to always improve the technology was at odds with providing a public service at the lowest possible cost. Why improve something if it does the job and it will cost more to change?

⁹ <http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=43207>.

This tension between the space agency and the weather-forecasting agency has been repeated around the world. In Europe, the first weather satellite, Meteosat, was developed and operated by Europe's NASA, the European Space Agency (ESA). Almost immediately, Europe's weather forecast agencies created a special agency called Eumetsat to take over Meteosat from ESA, and Eumetsat now owns and operates the satellites. In Japan, the Japan Meteorological Agency took over responsibility for weather satellites in the late 1990s when the first MTSAT geostationary weather satellite was launched. Previously, Japan's weather satellites had been owned and operated by the space agency NASDA (now called JAXA).

The space agencies haven't given up their control of weather satellites without a fight. In the USA, NASA is still responsible for developing new generations of weather satellites that NOAA then builds and operates. This arrangement has led to budget and schedule overruns as NASA tinkers with new technologies and NOAA is committed to providing the funds.

Europe has a similar situation but has (so far) avoided major overruns because Eumetsat gives a fixed amount of funds to ESA and tells ESA to develop the new generation system – any overruns are then ESA's problem to finance, which motivates ESA to prevent them happening.

The US Department of Defense (DoD) has its own LEO weather satellites, called the Defense Meteorological Satellites Program (DMSP). These 800-kg satellites take broadly similar measurements to the 1.4-ton NOAA satellites but have some encryption features to allow US forces to receive the data on the battlefield while denying it to the enemy. The similarity between the two satellites led President Clinton to decide in 1994 that the next generation of both would be common – called NPOESS¹⁰ (pronounced “en-pose”). That development was run by a project team reporting to DoD, NOAA and NASA, and the result of this confusing management chain has been delays, budget overruns, Congressional hearings, changes of contractors, but no satellites! Initially expected to produce six satellites, each carrying 10 sensors, over a 20-year period, NPOESS had a budget of \$8.4 billion. By 2006, the budget had gone up to \$12.6 billion but the number of satellites was down to four and the number of sensors to seven. The first interim satellite was supposed to be in orbit by 2006, but by the time the program was cancelled in February 2010, it was still a year and a half away from launch. The cancellation came even after the Obama Administration pumped an extra \$100 million into its 2010 budget. A Senate Appropriations Committee report called for the Administration “to disengage from its autopilot management style” and start taking responsible decisions – the cancellation followed. The US military and civilian weather satellites will now remain separate.

The DoD prudently still has two of its current satellites on order that will now be launched in 2012 and 2014, giving it time to plan how best to proceed for the long term.

¹⁰ NPOESS = National Polar Orbiting Environmental Satellite System.



Figure 15. NOAA Administrator Dr Jane Lubchenco claims that splitting DoD and NOAA weather satellite programs makes sense, but sees no inconsistency in NASA and NOAA programs remaining tightly intertwined. Credit: NASA photo by Bill Ingalls.

Unlike DoD, NOAA has no further versions of its existing satellites on order – the last was launched in early 2009. NOAA is left with the interim NPOESS satellite now due to be launched in 2011. The plan is that the first of the next-generation civilian NOAA satellites will be launched in 2014, funded by NOAA and procured by NASA, although past experience suggests that this timetable is optimistic. Commenting on the cancellation of the joint civil–military program, NOAA Administrator Jane Lubchenco (Figure 15) put a brave face on the debacle, saying that “this partitioning will enable both partners to do what they do well”.¹¹

The Defense Department’s weather satellite program has been successful for over 30 years. The NOAA–NASA civilian program is another matter. Inside the Defense Department, the weather satellite program was for many years run by the Strategic Air Command, whose mentality was operational rather than research. The weather satellites were designed to be fit for purpose, and to provide a day-in, day-out regular service. By contrast, the US spy satellites of the Cold War era were the responsibility of the Air Force Space Command, where pushing the boundary (in the technology sense) was integral to the culture. The spy satellites were often late and over budget, but they were technically very advanced.¹²

The US civilian weather satellites have tried to find a compromise between these two cultures, with NOAA as the end customer providing the regular service

¹¹ Brinton (2010g), Brinton (2010b), and Canan (2009).

¹² Arnold (2008).



Figure 16. Senior NOAA Official Dr Jack Hayes describes going from research to operations as “bridging the valley of death”.¹³ Credit: NOAA.

mentality and NASA as the development agency stretching the technology. The results have been mixed. A weakness in the arrangement is that NOAA pays NASA the cost of the development whatever the price; so, if NASA mismanages the development, NOAA pays. This contrasts with the situation in Europe in which the same sort of collaboration calls for Eumetsat (Europe’s NOAA) to pay a fixed amount to ESA (Europe’s NASA) so that overruns by ESA have to come out of its own budget. The cradle-to-grave cost of the next batch of US geostationary weather satellites, the GOES-R program, ballooned from \$6¼ billion to \$11 billion before a decision was made to delete one of its new instruments. Even so, the cost estimate is nearly \$8 billion and the launch of the first satellite has been put back from 2012 to 2015.¹⁴ NOAA admits to finding it difficult to turn advanced research into operational weather forecasts (Figure 16).

The current batch of US geostationary satellites comprises Geostationary Operational Environmental Satellite (GOES)-13 through GOES-15. Each weighs 3¼ tons when launched, although over 1½ tons of that is fuel, a lot of which is used to reach its final position in orbit, so it starts its useful life weighing about 2¼ tons. Its 8-m-long solar array produces 2 kW of electrical power – 2½ times that of the low-orbit NOAA satellites. The last in this batch, costing about \$500 million, was

¹³ Iannotta (2008).

¹⁴ Hayes (2008).

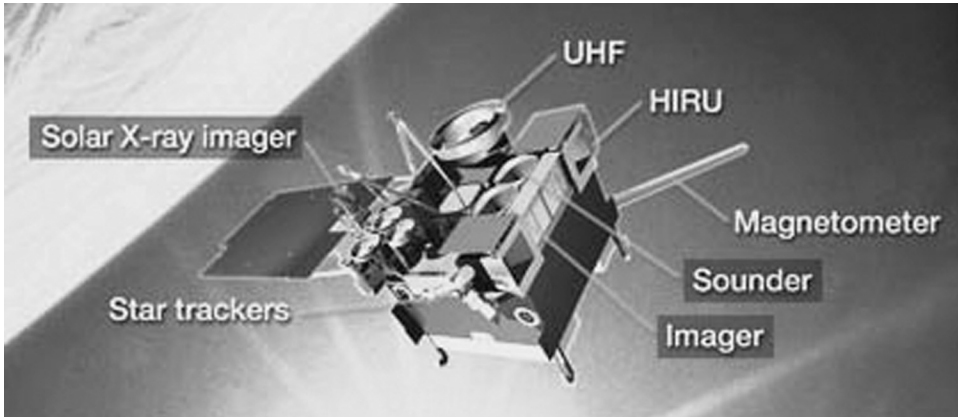


Figure 17. Artist's impression of GOES-13 in orbit. The circular openings of the imager and sounder on the right point to the earth above and to the left in this view. At 36,000-km altitude, the earth should be about 20 times the size of the moon as we see it, so the artist has drawn the earth much too large – almost as if it would fill the sky. The annotation is explained in the text. Credit: NASAscience.

launched in March 2010. There will now be a 5-year wait for the first of the new and improved batch, as mentioned above.

The artist's impression of GOES-13 in Figure 17 illustrates some of the key features of the satellite. UHF is the antenna that receives emergency beacon signals and data from weather stations. HIRU is a gyroscopic unit that, together with the star trackers, keeps the satellite stable and pointing correctly. The solar X-ray imager monitors outbursts of the sun and the magnetometer on the end of the long boom measures the magnetic field of outer space – the long boom avoids it being corrupted by equipment on the satellite. The imager (camera) produces images in five colors (or “channels”) of the earth every half hour or so (more frequently if smaller images are taken). Each pixel in its infrared images is 4 km on a side and 1 km on a side in the visible image. The sounder takes a single pixel image in 19 channels, all but one in the infrared, from which we can calculate the temperature, humidity and key constituents of narrow areas of the atmosphere – its pixel size is about 10 times larger (more blurred) than that of the imager – an animation of how a sounder works is available on NASA's website.¹⁵

There's more than one way to skin a cat, and while Japan's MTSAT satellites look pretty similar to the USA's GOES, Europe's geostationary satellite, Meteosat, looks nothing like either MTSAT or GOES. Figure 18 is an artist's impression of the latest Meteosat in orbit. It weighs 2 tons when launched, of which nearly half is fuel. Unlike the box-shaped GOES in Figure 17, Meteosat is a cylinder about 2½ m high and ¾ m in diameter. While GOES stays rock steady as it captures images of the

¹⁵ www.aqua.nasa.gov/about/instrument_amsu.php.

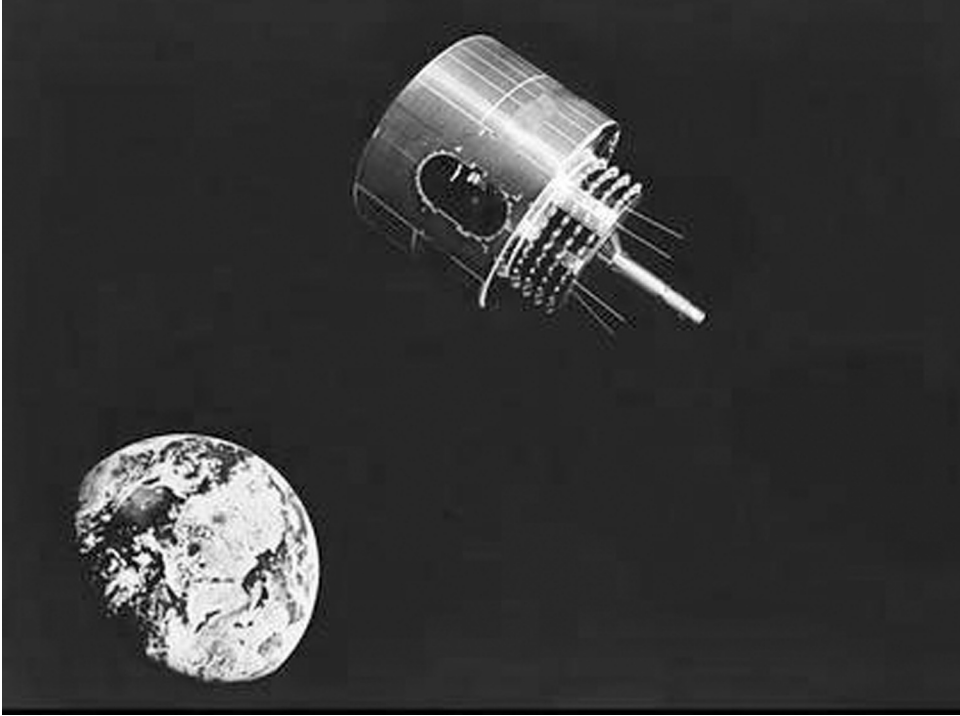


Figure 18. Artist's impression of a second-generation Meteosat in orbit; the first of this series, Meteosat-8, was launched in 2002 followed by Meteosat-9 in 2005. Credit: ESA/Eumetsat.

earth, Meteosat spins at 90 rpm. Its camera stares out through the elliptical window that you can see in Figure 18. Each time the satellite whizzes round, the window is looking at the earth for about 35 milliseconds it then spends 600+ milliseconds staring into space. During those 600 milliseconds, the picture captured during the 35 milliseconds is radioed to earth. The solar cells that provide its 600 W of electrical power are glued to the side of the cylinder rather than being on a dedicated solar panel like GOES or MTSAT.

Spinning is inherently a very stable condition – that is why a spinning top stays upright whereas a stationary one falls over. Meteosat takes advantage of this and avoids the need for the sophisticated stabilization equipment that GOES and MTSAT require. Meteosat's radio antennas are deceptively clever; the “necklace” round the narrow part of the cylinder is a radio antenna that sends radio signals in the direction of earth – electronically cancelling out the spinning movement precisely. Despite looking somewhat old-fashioned, Meteosat has a camera that takes images in 12 channels compared with the five on GOES and MTSAT – Meteosat is therefore the most sophisticated of all the weather satellites in geostationary orbit, at least as concerns taking the most information-rich images. The first of the current generation of Meteosats was launched in 2005 and cost about

\$630 million. The series of three satellites plus the cost of rockets to launch them, dedicated ground facilities and operations staff for 12 years came to about \$2 billion.

Mind you, Europe has ways of its own to make a muddle of things. The next generation of European weather satellites, the so-called Meteosat Third Generation satellites caused a political furore in the first half of 2010. The early phases went according to the book, with the European Space Agency and Eumetsat collaborating to agree what the satellite would do and obtaining quotes from industry to build the system. The best and cheapest (by about \$200 million) industry proposal for the \$1 $\frac{3}{4}$ billion contract was led by a French company, TAS, with a German company, OHB, earmarked for a large subcontract. The losing bidder had the reverse political pecking order – Astrium Germany as prime contractor, with Astrium France as its supplier. German industry gets about the same number of contracts either way, but the German Government wanted its industry to lead the project and in a fit of pique, vetoed the award of the contract to TAS at the Eumetsat Council.¹⁶ After much German posturing, the French-led bid was accepted but in a way that gave German industry a larger and face-saving role and a small increase in the cost. Another scenario that was considered was for some sort of co-leadership to be set up between France's TAS and Germany's Astrium. This formula was tried for the Galileo satellite navigation program, resulting in costs doubling and schedules slipping by several years as the two rivals fought bitterly over every nut and bolt in the program, and then both companies lost out to a third company when the contract was re-tendered. In the case of Meteosat Third Generation, Europe's politicians avoided a political compromise that ignores commercial realities and fudges industrial responsibility.

The same Meteosat Third Generation project contains another example of Europe's ability to shoot itself in the foot. British companies were barred from competing for the contract mentioned above because two government departments bickered over which of them should pay for the development contract. The Ministry of Defence has to pay for the operational phase at Eumetsat, since it owns the UK Met Office (the national weather service), but feels that the Business Department should pay for the development phase that is managed by the European Space Agency. The two departments failed to reach agreement, so there is no British money in the European Space Agency part of the project, thus barring British industry from it. The Eumetsat part represents three-quarters of the total, so the British money paid into that fund will go towards paying companies in France, Germany and the rest of Europe that have been part of the development phase. British tax payers might wonder whether their civil servants are delivering value for money in this instance.

Meteosat Third Generation will provide sounder information as well as imaging, which the US GOES does already. The idea of a sounder is to measure the

¹⁶ de Selding (2010a), de Selding (2010c), personal communications; Portugal also vetoed the award initially but for reasons related to its perilous government finances.

temperature and humidity of the air at various altitudes. A satellite can do this because molecules in the air radiate very faintly in a characteristic way that depends on their temperature. The “color” of the radiation (more correctly, its wavelength or frequency) tells you what height it is coming from. The instrument on the satellite looks downward to measure the radiation at several “colors” – by analogy with a ship, it takes a “sounding”, hence the name “sounder” for this type of instrument. The instrument then points slightly to the right, say, and takes another sounding and continues like that to build up a picture of the temperature of the atmosphere below. A computer animation on the NASA website illustrates a typical sounder in action (see www.aqua.nasa.gov/about/instrument_amsu.php).

Some “colors” of radiation are affected by humidity in the air, so this information can be used to provide a map of humidity at various heights in the atmosphere. Weather forecasters increasingly use the information from sounders in helping to predict the weather.

Unlike the US GOES, the Europeans will not squeeze the sounder onto the same satellite as the imaging camera, but will fly it on a separate satellite. Over its 20-year lifespan, the Meteosat Third Generation’s \$4½ billion budget will pay for four imaging satellites and two with sounders. Separating the sounder from the imager means you have to build extra satellites and buy rockets to launch them, but it brings two important benefits. First and most obviously, each satellite is simpler, smaller, cheaper, lighter (thus cheaper to launch) and less likely to run over budget than a complex combined imaging/sounder satellite. The sounder is constantly scanning from side to side, creating jitter in the imager, so a satellite containing both imager and sounder requires special insulating arrangements to reduce this jitter. Second, and perhaps less obviously, if, say, the sounder fails but the imager is still working, you just launch a replacement sounder – vice versa if the imager fails. With the GOES and MTSAT approach in which sounder and imager are on the same satellite, replacing a sounder means launching a whole new expensive imager plus sounder, one of which is not really needed.

Figures 19 and 20 illustrate the power of geostationary satellites to provide continental-scale weather information. Figure 19 is a so-called false color image of North America taken by the US GOES-12 satellite. The image in the visible channel is a black-and-white image, so infrared images are combined with it to create a natural-looking but “false” color image. A new image every half hour enables emergency authorities to track hurricanes as they move across the map. Figure 20 is a black-and-white image taken by Japan’s MTSAT-1R satellite, in which the sea and land have been colored in by computer.

Each GOES satellite has an expected life of 10 years and, often, they keep working for longer than that. Occasionally, one fails before it should and leaves a gap in the weather information. One of the advantages of coordinating the satellites of Europe, the USA, Japan, etc. is then evident, in that one of the other countries can lend a satellite to fill in for the failed one for a while. Over the years, the USA has borrowed one from Europe, and Japan and Europe have each borrowed one from the USA. As is evident in Table 2, there appear to be more than enough weather satellites in geostationary orbit at the moment; you need about four to cover the

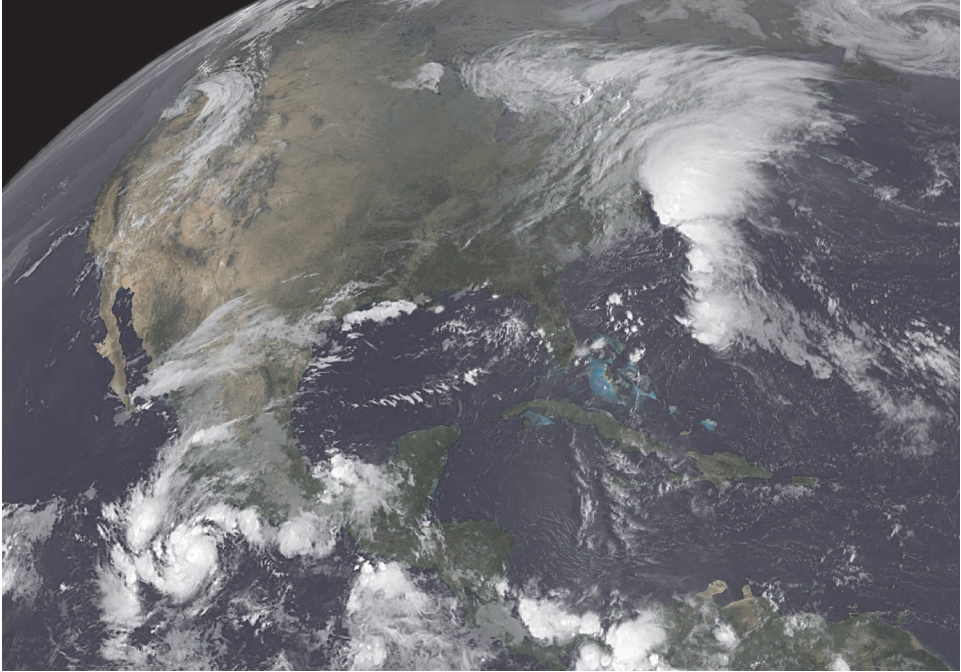


Figure 19. GOES-12 captured a dying Tropical Storm Danny on the US east coast (top right) and an explosive Tropical Storm (later Hurricane) Jimena on the Mexican west coast (bottom left) on August 29th 2009. Credit: NASA/GOES Project.

whole globe, and there are currently 16 in orbit, although some are only partially working.

Another feature of the coordination is that each satellite relays weather data from weather stations on the sea, on ships and on aircraft, irrespective of the origin of the weather station. This is particularly convenient for airborne stations, since a long-distance aircraft may well move from the coverage zone of one satellite to that of another in the course of a single flight.

The world has therefore got itself a global weather satellite system without the need for a global weather satellite organization. The various weather agencies representing the satellites in Tables 1 and 2 meet from time to time to discuss their plans and to agree how they will coordinate among themselves.¹⁷ The arrangement is hardly perfect, as witnessed by the considerable over-supply of geostationary satellites, but each country decides what it wants to contribute and then just gets on with it. The information from the satellites is shared among the world's weather bureaux free of charge. India is a partial exception to this free-access policy. Until

¹⁷ The group calls itself the Coordination Group for Meteorological Satellites (CGMS); see http://cgms.wmo.int/CGMS_home.html.

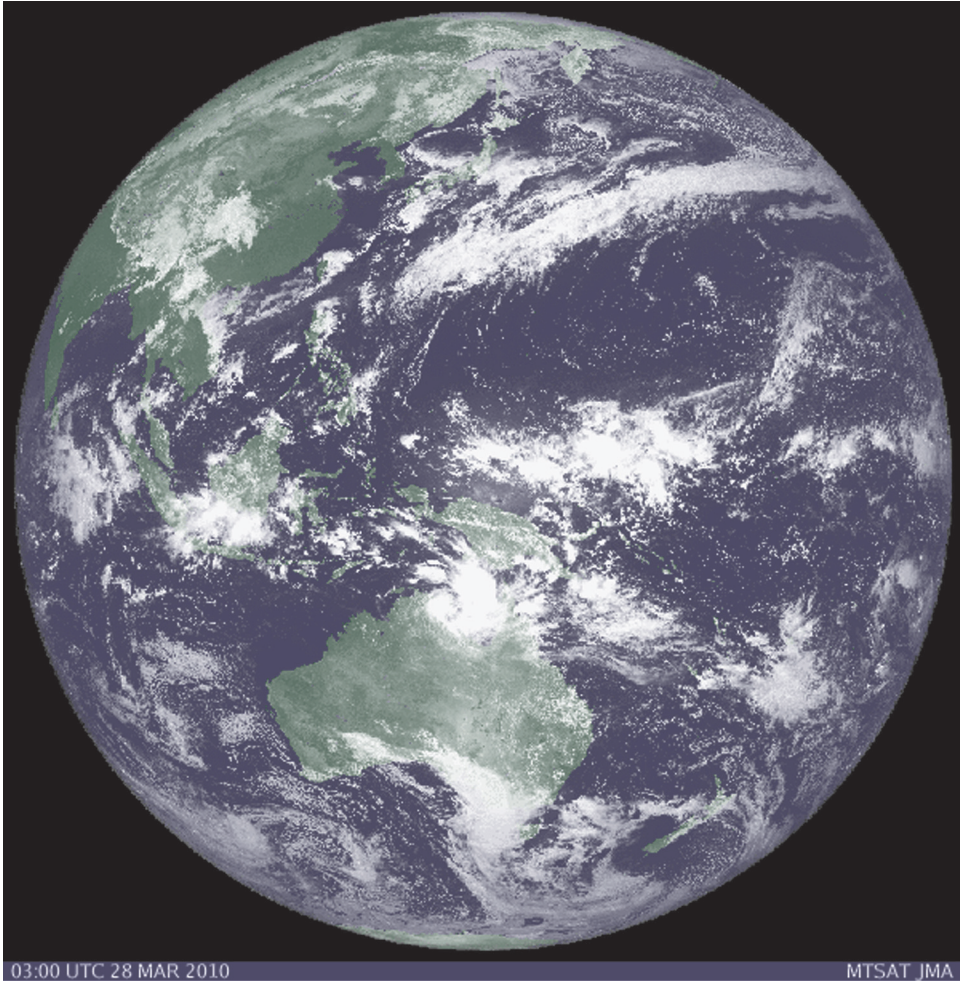


Figure 20. Japan’s MTSAT-1R satellite monitors the weather on March 28th 2010 from India on the extreme left to the central Pacific Ocean, and from Antarctica in the south to the Arctic Ocean in the north. Tropical Cyclone Paul is generating winds of up to 90 mph (140 kph) in northern Australia in the lower center.

1999, India encrypted the data sent back by its weather satellites so that only organizations inside India could access it. In 1997, NASA and NOAA signed an agreement with India to allow INSAT data to be accessed by those two US agencies but by no one else, and by 1999, data were being received in the USA. Even then, the data made available to the US agencies are 3 days old, not in real time.¹⁸ In Geneva, the World Meteorological Organisation (WMO), which is an

¹⁸ Chesters (2009).

agency of the UN, keeps a watching brief on all of this, but, in practice, plays no significant role.

GROUND FACILITIES

Speaking of budget overruns – while you might expect some examples in the world of rocket science and satellites, it may come as a surprise to find that the ground facilities are often just as late and over budget.

Take, for example, the software to remove defects from the images provided by geostationary satellites mentioned above. Europe's latest geostationary weather satellite, called Meteosat Second Generation (MSG), needed that kind of software in the control center in Germany. Sadly, the satellite manufacturer that Eumetsat chose to supply that software made a complete mess of it. The contract said that the software was to be delivered a year or so before the launch of the satellite, but it ended up being delivered about 5 years late. Eumetsat decided they couldn't launch the satellite if this particular software wasn't available because you have to remove the defects in the images to get reliable weather information from them. Having delayed the launch by 2 years and incurring tens of millions in payments to the launch company, ESA and the satellite manufacturers (who had to store the satellite and keep their team of experts on stand-by), Eumetsat decided to go ahead, even though the software was still not ready. For the first 2 years after the launch, Eumetsat had to use a stop-gap piece of software that allowed them to produce one set of good images and data a day. Most of the other software for MSG was also delivered late, although not so late as to cause the delay of the launch.

A similar fate befell NOAA's new-generation geostationary satellite system in the 1990s. The satellite was launched as planned, but it was about a year after that before the images and data were of the expected quality due to errors in the defect-removal software.

Happily, some software is delivered on time – the defect-removal software for Japan's MTSAT new-generation geostationary weather satellite worked perfectly first time. And although Europe's MSG suffered from several software snafus, the sophisticated software that automatically extracts wind information (by tracking clouds between images) was on time and working perfectly.¹⁹ The reasons why some suppliers of software mess up while others get it right is a subject for another book – one lesson to learn is that just because a company can build ultra complex and sophisticated satellites doesn't mean they can supply software; as so often in life, it is a case of horses for courses.

¹⁹ The successful MSG and MTSAT systems quoted were both supplied by the team I work with at Logica plc.

HURRICANES, TYPHOONS AND TORNADOES

Satellites have shown themselves particularly useful in alerting communities to the dangers of incoming hurricanes and typhoons.²⁰ A storm earns this title if its wind speeds exceed 74 mph (119 kph). They start as ordinary storms in the tropical ocean regions, where geostationary satellites can spot their signature spiral shape. If the waters are warm enough, the storm will strengthen and its winds will pick up speed. Satellites allow forecasters to spot the emerging storms, to follow their path and growth, to monitor the temperature of the sea surface and to direct planes and ships to take more detailed measurements if necessary.

Forecasting the path and growth of these big storms is not yet a precise science. One of the factors to consider is the temperature of the sea in the region – the hotter that is, the more likely the storm will grow. Satellite measurements of sea surface temperature are the primary source of this information in most cases.

Tornadoes are a much more transient form of storm, arising and disappearing in hours rather than the days or weeks of hurricanes. The wind speeds in a tornado are phenomenally high, up to 500 kph, hence their unstoppable destructive effect. But they are small in extent compared to a hurricane – less than 100 m wide as opposed to the 100 km or more of a hurricane. Satellites therefore have a tough time spotting tornadoes – the typical geostationary satellite that is constantly watching the USA has a pixel size of a few kilometers – much too big to spot an individual tornado. The best the weather man or woman can do is to spot weather patterns that are likely to spawn tornadoes, but not the tornadoes themselves.

Designs of geostationary satellites that could spot an individual tornado are on the drawing board – but are likely to stay there for quite a while due to their high cost. The military, too, would like a geostationary satellite that could pick out details on the ground and we will discuss the challenges in creating such satellites when we come to discuss military surveillance in Chapter 8.

²⁰ Hurricane is the name of this type of storm in the Atlantic Ocean, typhoon in East Asia, (severe) tropical cyclone or (severe) tropical storm elsewhere; see www.aoml.noaa.gov/hrd/tcfaq/A1.html.