RECOMMENDATION ITU-R RA.1750-0*

Mutual planning between the Earth exploration-satellite service (active) and the radio astronomy service in the 94 GHz and 130 GHz bands

(2006)

Scope

This Recommendation describes measures to be taken by the Earth exploration-satellite service (EESS) (active) and the radio astronomy service (RAS) to minimize the potential impact of 94 GHz and 130 GHz EESS (active) cloud-mapping radars upon RAS observations in adjacent bands.

The ITU Radiocommunications Assembly,

considering

a) that current and future satellite-borne cloud radar mapping experiments of the Earth exploration-satellite service (EESS) (active) in the 94 GHz and 130 GHz bands shared with the radio astronomy service (RAS) are expected to return important scientific results on global climate;

b) that the RAS is expected to continue studying important scientific questions in the 94 and 130 GHz bands shared with EESS (active);

c) that at millimetre wavelengths, the directive antenna gain available both on a satellite and at RAS ground stations is very high, creating the possibility of very strong main beam-to-main beam coupling between a satellite transmitter antenna and an RAS antenna;

d) that in order to obtain adequate radar echoes from atmospheric phenomena, orbiting radars of the EESS (active) require very high e.i.r.p. that has the potential to cause physical damage to the sensitive RAS receivers in the case of main beam-to-beam coupling;

e) that individual RAS instruments may consist of dozens or even hundreds of co-directed antennas, some or all of which may be co-located within the main beam of an EESS (active) satellite on an instantaneous basis, greatly multiplying the consequences of a main beam-to-main beam encounter;

f) that at millimetre wavelengths, current technology does not permit the construction of high performance stop band filters with sufficiently low insertion loss within the wanted passband;

g) that receivers used by the RAS at millimetre wavelengths must employ state-of-the-art technology in order to be sufficiently sensitive to carry out original astronomical research and that such technology currently allows very limited dynamic range with a relatively low saturation threshold;

h) that because of the expected high e.i.r.p. of the cloud radar, main beam-to-sidelobe coupling between the satellite transmitter and the RAS station may cause saturation of the RAS receiver, potentially preventing observations at an RAS station for a significant fraction of the time that the active cloud radar satellite is above the local horizon;

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[*] Radiocommunication Study Group 7 made editorial amendments to this Recommendation in the year 2017 in accordance with Resolution ITU-R 1.

j) that current technology now permits RAS stations to be outfitted with multi-element focal plane array receiver systems having full main beam sensitivity subtending 1 000 times the angular area of a single pixel receiver,

further considering

a) that of necessity, millimetre-wave RAS observatories operate at the frequencies shared with EESS (active) only under dry-clear conditions so that atmospheric attenuation gives no protection to the RAS station from the satellite radar;

b) that mutual planning between operators of the EESS (active) and radio astronomers is essential in order to avoid damage to the RAS instrumentation, and in order to maintain the integrity both the RAS and the EESS (active) data to the maximum extent possible;

c) that the Space Frequency Coordination Group (SFCG) and the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF) developed a mutual planning procedure[1] between SFCG member agencies and the radio astronomy observatories for space-borne cloud radars to be operated in the band at 94–94.1 GHz,

recommends

1 that as early as possible in the design cycle of such an EESS (active) cloud radar system, contact should be established between the EESS (active) designers and operators and with radio astronomy sites – the international organization IUCAF may provide the initial link between the EESS operators and potentially affected radio astronomy observatories;

2 that close contact between radio astronomers and the operators of the EESS (active) system should be maintained throughout the design and operational life-cycles of all systems which are subject to sharing in the 94 GHz and 130 GHz bands such that each party is apprised of pertinent developments within the other;

3 that the design and operation of systems operating in each service should be performed so as to account for sharing to the greatest practicable extent;

4 that the considerations relevant to sharing given in Annex 1 should be taken into account in the design and operations of such systems;

5 that the example provided in Annex 2 of the impact upon one instrument operating in the radio astronomy service from one satellite operating in the EESS (active) should be taken into account in the design and operation of stations of both services.

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[1] See Resolution 24-2 of the SFCG at: https://www.sfcgonline.org/resolutions/RES SFCG 24-2 (94 GHz allocation use).pdf

Annex 1

Considerations relevant to the design and operation of systems intended for sharing between EESS (active) and RAS in the 94 GHz and 130 GHz bands

For the EESS (active):

- An active radar system should be designed according to best engineering practices to minimize unwanted emissions, and to minimise off-axis emission from the radar antenna into sidelobes.
- So far as is practicable, an EESS (active) system should be designed and operated in such a way as to avoid transmitting through its main beam directly at stations of the RAS.
- Operators of an EESS (active) system should ensure that all operational help possible be given to RAS stations, such as providing timely orbital details of the satellite radar.

For the RAS:

- RAS stations should be designed to be able to prevent their antennas from pointing directly at the orbiting radar, by flexible dynamic scheduling of observations or other means.
- RAS stations should provide the means to protect their receivers from physical damage if complete avoidance of main beam encounters is impracticable.
- To the extent reasonably possible, without compromising the capability of the RAS station, RAS receiver systems should be designed to have a high tolerance for damage from received high power transmissions, and to possess as high a dynamic range as is feasible.
- RAS antennas should be designed with the lowest practicable sidelobe levels so as to permit observations to continue while the satellite radar is above the local horizon, although not directing its radar towards the RAS station.
- RAS data acquisition systems should be designed to log or flag instances of potential interference from the orbiting radar, based on known RAS and satellite operational parameters.
- RAS should continue to devote resources to extending the possibilities of real time or post-observation RFI mitigation techniques.

Annex 2

An example of considerations relevant to sharing to be taken into account in the design and operations of systems of the RAS and EESS (active) in the 94 GHz band

The CloudSat and implications for the Atacama Large Millimeter Array (ALMA)

Abstract

The Atacama Large Millimeter Array (ALMA) observatory is under construction in northern Chile, and will become the world's prime observatory at mm and sub-mm wavelengths. CloudSat is a downward-looking 94 GHz satellite-borne radar, due for launch in 2005. The peak e.i.r.p. of the radar beam is some 4×10^9 W, which is sufficient to damage ALMA receivers on the ground if ALMA antennas and the orbiting radar ever look directly at each other. Although the likelihood of this happening is very small, ALMA does need to take some operational precautions to avoid receiver damage, and to flag data that will be contaminated by radar interference.

The ALMA radio astronomy facility

ALMA is an international millimetre and sub-millimetre wavelength telescope, being an equal partnership between Europe, North America and Japan, in cooperation with the Republic of Chile.

Important points to note about ALMA are:

- Up to 64 12-m antennas located at an elevation of 5 000 m in Llano de Chajnantor, Chile.
- Imaging instrument in all atmospheric windows between 10 mm and 350 microns (31.3 GHz to 950 GHz).
- Array configurations from approximately 150 m to 10 km.
- Spatial resolution of 10 milliarcseconds, 10 times better than the Hubble Space Telescope.
- The ability to image sources arcminutes to degrees across at one arcsecond resolution.
- Velocity resolution under 0.05 km/s.
- Fast and flexible imaging instrument.
- Largest and most sensitive instrument in the world at millimetre and submillimetre wavelengths.

The cloud mapping radar mission

CloudSat is the first spaceborne radar to make use of the 94 GHz allocation. It is part of the "A-train" constellation, consisting of five satellites, most of which (apart from CloudSat) are passive sensing satellites. In order of orbital formation, the satellites are Aqua, Cloud Mapping Radar, Calipso, Parasol and Aura. Parasol, Aqua and Aura are already in orbit, with CloudSat itself now to be launched in 2005. All satellites will have similar orbits, arranged specifically to have identical ground tracks, separated by only some seconds of time. Details of the scientific mission are as follows:

CloudSat is a satellite experiment designed to measure the vertical structure of clouds from space. Once launched, CloudSat will orbit in formation as part of a constellation of satellites (the A-Train) that includes NASA's Aqua and Aura satellites, a NASA-CNES lidar satellite (CALIPSO), and a CNES satellite carrying a polarimeter (PARASOL). A unique feature that CloudSat brings to this constellation is the ability to fly a precise orbit enabling the fields of view of the CloudSat radar to be overlapped with the CALIPSO lidar footprint and the other measurements of the constellation. The precision and near simultaneity of this overlap creates a unique multisatellite observing system for studying the atmospheric processes essential to the hydrological cycle.

The vertical profiles of cloud properties provided by CloudSat on the global scale fill a critical gap in the investigation of feedback mechanisms linking clouds to climate. Measuring these profiles requires a combination of active and passive instruments, and this will be achieved by combining the radar data of CloudSat with data from other active and passive sensors of the constellation.

Technical details of CloudSat

The CloudSat radar operates at 94.05 GHz, from a sun synchronous polar orbit with a height of 705 km; the ground tracks of the orbit (see below) repeat precisely every 16 days. Peak radar transmitter power is 1 800 W, degrading to 1500 W at the end of its lifetime, into an antenna with 63 dBi gain, giving approximately 4×10^9 W effective radiated power (e.i.r.p.). Polarization is linear. The radar points along the geodetic nadir within 0.07°. The nominal footprint of the radar beam on the ground is ~1.4 km in diameter, but the extent of the footprint to the first nulls in the pattern is 3 km. Pointing knowledge is 0.053° and pointing control is around 1 km. ALMA, with a diameter of 14 km, subtends an angle of 1.14° as seen from the satellite. The actual ground track may have a cross-track error ±10 km, caused by an unpredictable component of atmospheric drag perturbing the orbit. The radar pulse length is approximately 3.3 μs, and the pulse repetition frequency (PRF) varies from 3 700 to 4 300 Hz, giving mean radar transmitter power of about 25 W.

The CloudSat antenna is an offset parabola and has a beamwidth of 0.108°, with a boresight gain of 63 dBi. The distance to first null in the pattern is ±0.125°. The first major sidelobe, 0.2° from boresight, has a gain of 47 dBi. The antenna gain reaches 0 dBi at about ±6.4°, and beyond about ±11° the antenna response is no greater than about –12 dBi.

Because the radar beam is always directed downwards, along the local gravitational vector, the only possibility of ALMA antennas looking directly into the radar beam is if they are pointed at the zenith, as the radar flies directly over the site. This is an unlikely occurrence. The CloudSat beam will occasionally be directed away from the nadir, for calibration purposes, but this measurement will always be carried out over ocean, so should not be an issue for ALMA.

CloudSat's orbit

Because of the nadir-pointing radar beam, only the ground directly below the satellite, the sub-satellite point, is directly illuminated. The orbital period is 98.8 min, giving ~15 orbits per day, and the inclination of the orbit is 98.2°; this is a sun synchronous orbit, arranged so that the ground tracks repeat exactly every 16 days. At ALMA there will be 5 or 6 orbits per day which rise above the horizon. After the 16-day period, there will have been 233 orbits giving ground tracks covering the earth regularly every 170 km (at the equator) – with of course an equal number of ascending and descending passes.

CloudSat will have an orbit similar to the lead satellite of the A-Train, AQUA, which is already in orbit. In the following discussion, the AQUA orbital parameters have been used as being representative of the future CloudSat. These AQUA elements are likely to remain representative, but may not correspond to the precise CloudSat orbit.

The orbital elements for AQUA (July 26 2004) that is used in the simulations below are:

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1 27424U 02022A  04207.86676596  0.00000493 00000-0  11941-3 0  7961
2 27424  98.2212 147.2739 0001153  89.3378 270.7995 14.57121862118484
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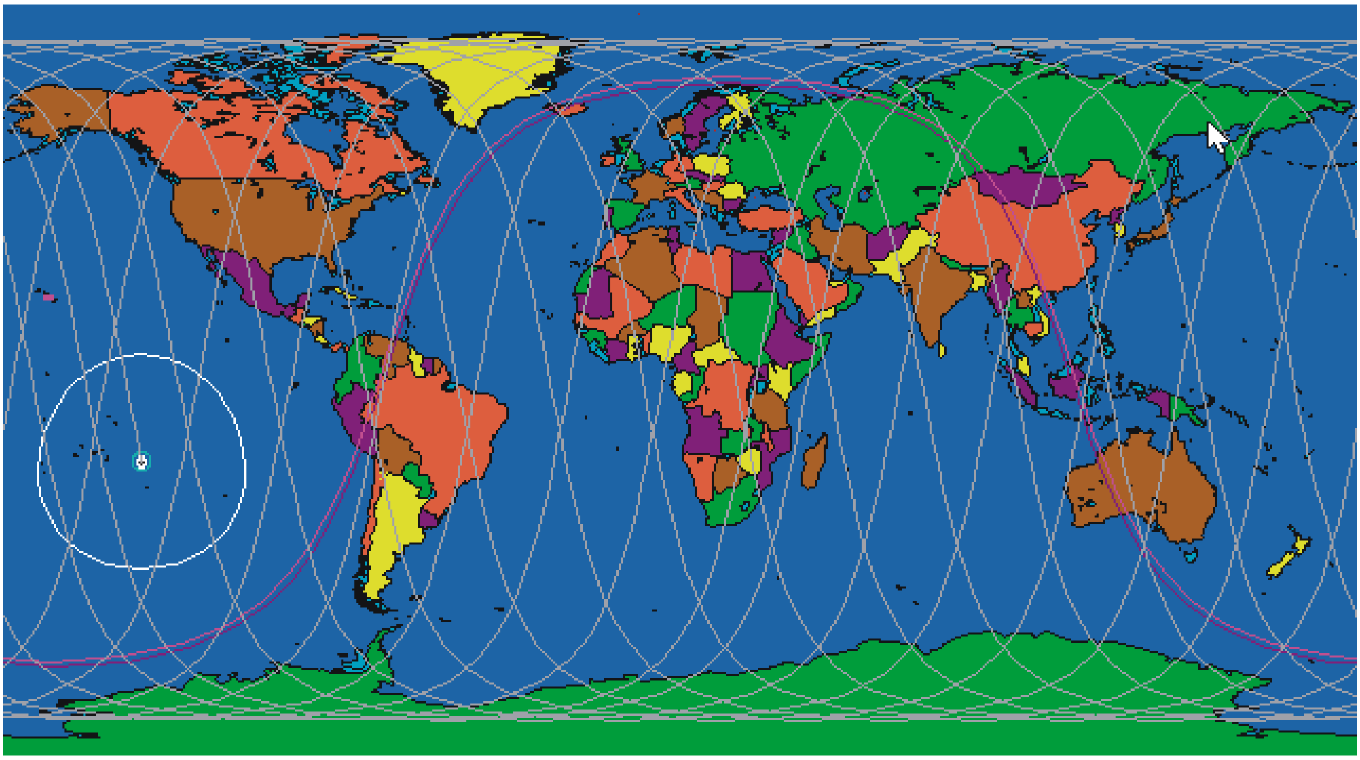
Most standard satellite tracking programs expect this format. Derived from this, the orbital period of AQUA is currently 98.83 min and the inclination of the orbit 98.221°. The height above ground is approximately 705 km.

The following orbital analyses used a variety of different software. Figure 1 shows a map of the world with AQUA ground tracks plotted after 24 h of orbit. Note that, because of the inclination of the orbit (98.2°), no ground tracks reach beyond latitudes ±81.8°. Both ascending and descending orbital tracks are shown.

FIGURE 1

AQUA tracks over 24 h



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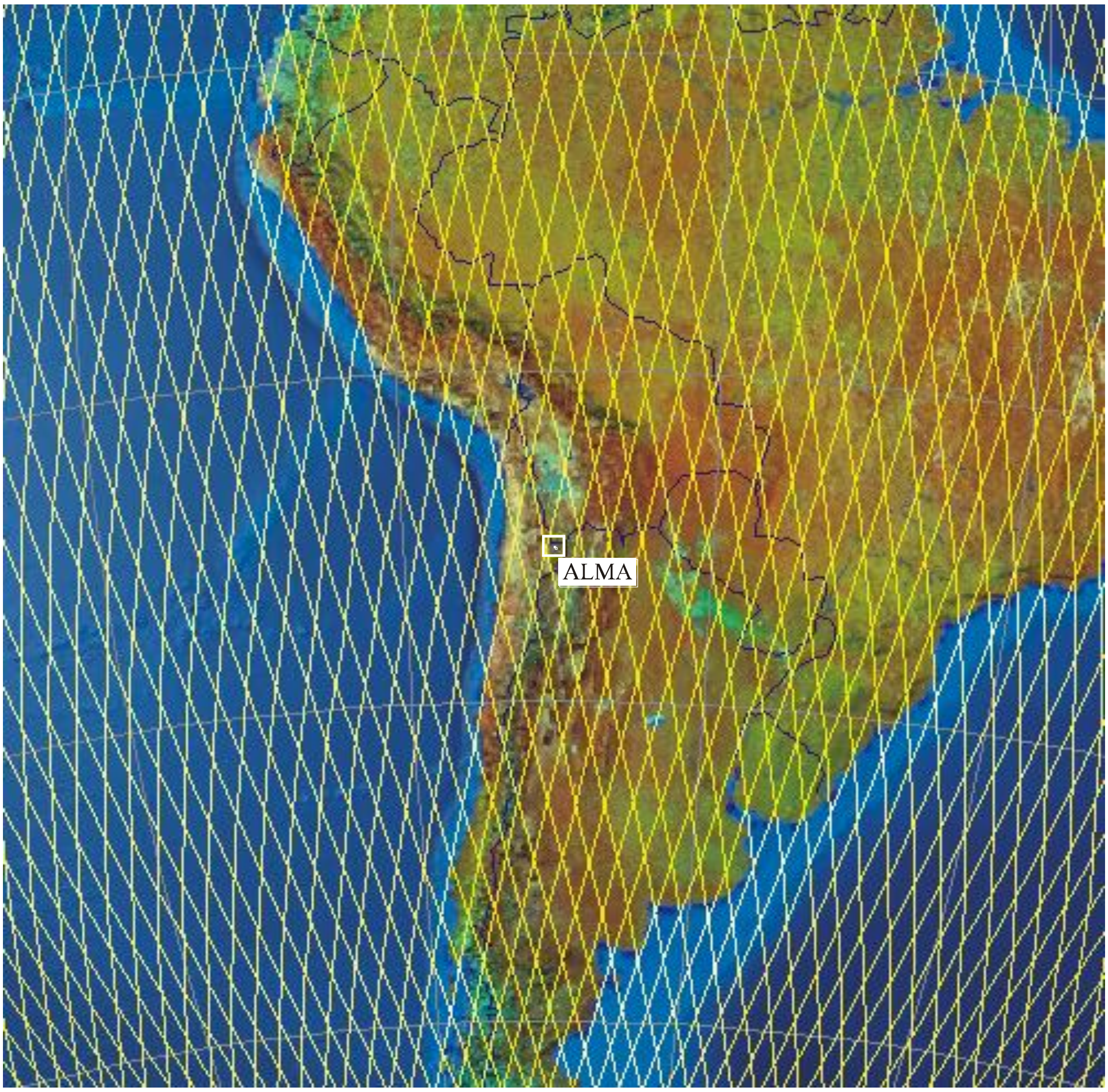
Note the light circle delineating the typical extent of the terrestrial horizon visible from AQUA.

Figure 2 shows a view of South America, with the ALMA coordinates marked, and showing the full set of 16 days of ground track. For these orbital parameters, these represent ALL ground tracks from the satellite; the tracks repeat precisely every 16 days. As with Figs. 1 and 3, the ascending (S-N) orbits slant from lower right to upper left, while the descending (N-S) orbits slant from upper right to lower left.

FIGURE 2

Ground tracks of AQUA over a full 16-day period, with the position of ALMA marked on a map of South America



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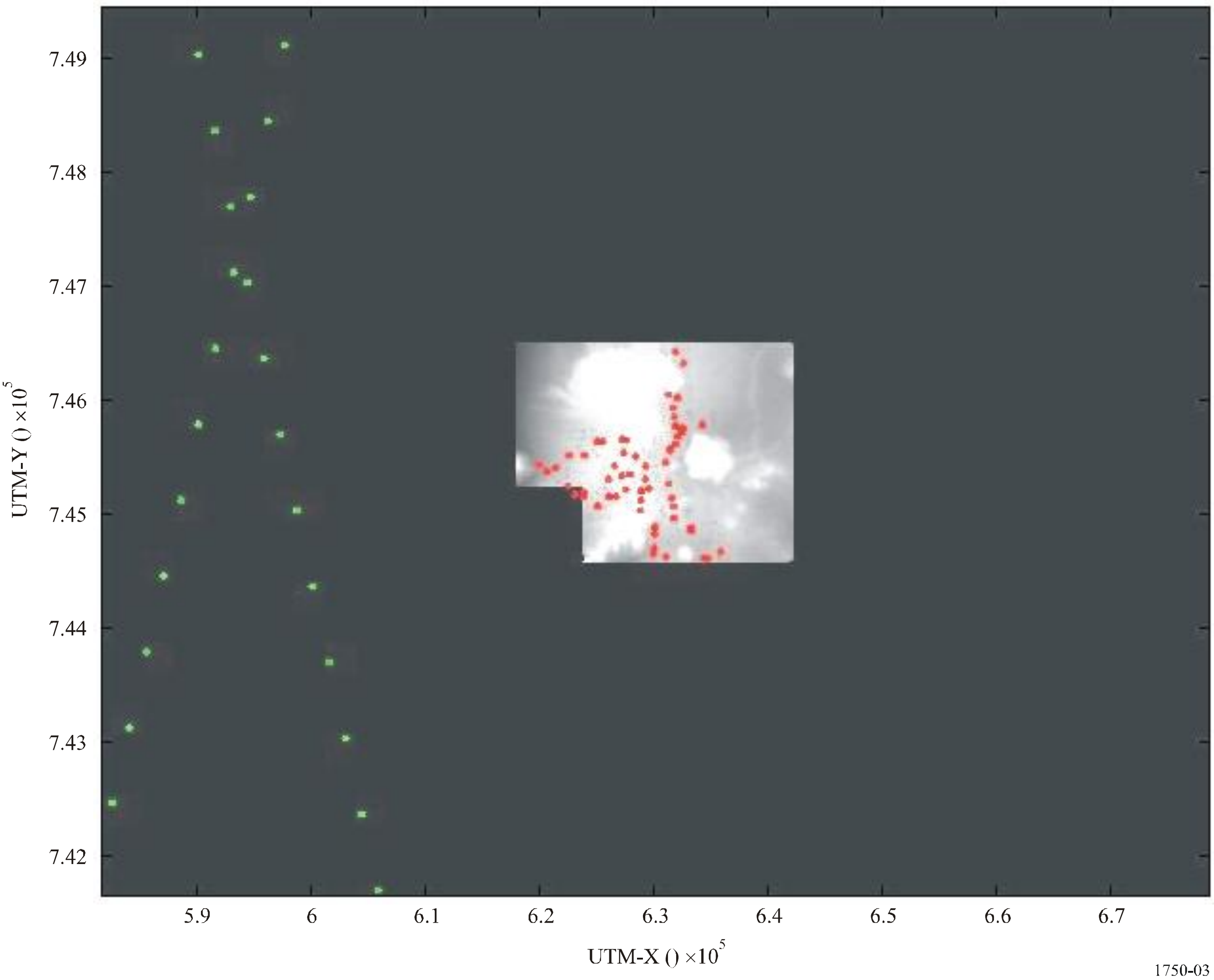
Subsequent tracks repeat precisely every 16 days. The final CloudSat ground tracks will be similar, but not identical.

Figure 3 plots in more detail the ground tracks that pass close to ALMA over any 16-day period.

FIGURE 3

Ground tracks of AQUA: the green dots the left mark the closest approach of AQUA ground tracks to the ALMA array; these marks are separated by one second of time along the AQUA orbit, although the radar transmission is of course continuous



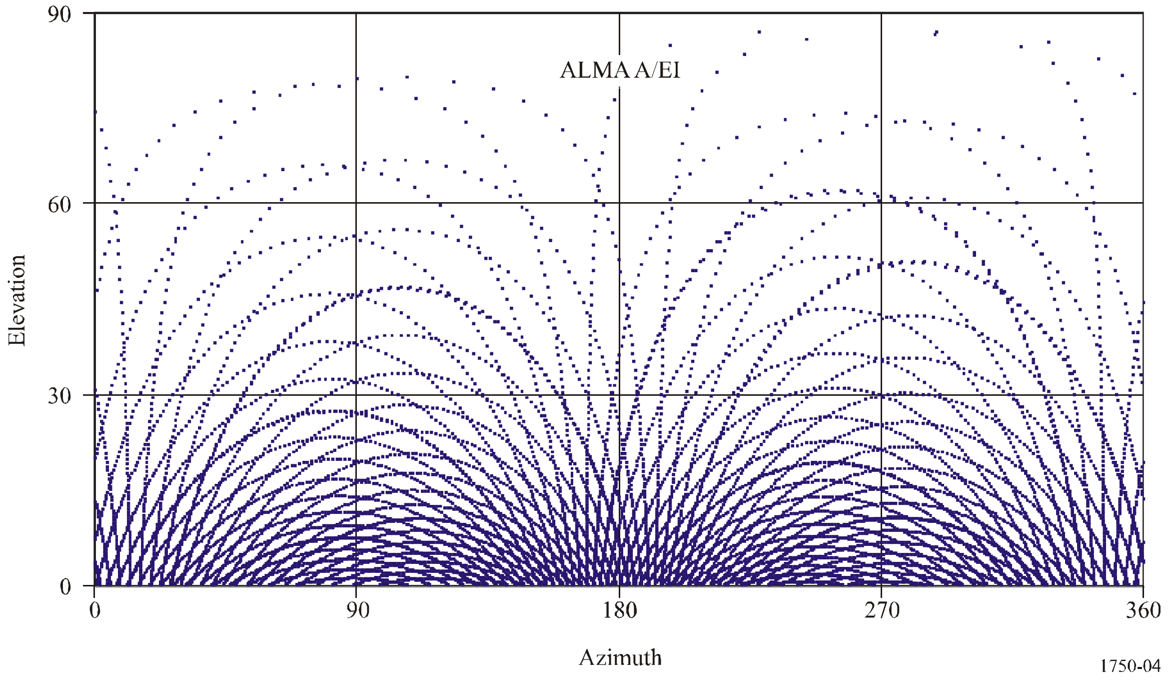
The central red dots mark antenna positions in the extended ALMA configuration. The axes tick labels show UTM coordinates, with ticks every 10 km. The ground track of AQUA approaches within ~30 km of the center of ALMA. Of the two ground tracks shown, one is ascending (S-N) and the other descending (N-S). These 2 tracks are separated in time by about 8 days, but both repeat every 16 days.

These orbital tracks are to be regarded as representative; the final CloudSat orbit ground track could pass closer to or further away from ALMA.

Figure 4 plots the azimuth and elevation of all satellite tracks seen from ALMA, over a 16-day period.

FIGURE 4

Azimuth-elevation tracks of AQUA seen at ALMA over a 16-day period



The satellite's Azimuth and Elevation is marked for every 5 s of each satellite pass. The maximum elevation is less than 3° from the zenith at the center of ALMA. Although this AQUA orbit may not correspond exactly to the final CloudSat orbit, the statistics of satellite positions will be very similar.

Power received by an ALMA antenna and the implication for receiver survival

There are four classes of coupling between the CloudSat radar and ALMA antenna beams:

Class 1: Far antenna sidelobe to far sidelobe interaction. Assuming 0 dBi sidelobes for both the radar and the ALMA antennas, for 705 km spacing (the CloudSat orbital height) and 94 GHz, the propagation loss (between isotropic antennas) is 188.9 dB. For a transmitter (peak) power of 1.8 kW = 32.5 dBW, the power picked up in the receiving antenna is 32.5-188.9 = –156.4 dBW. Compare this with the system noise power in a receiver with bandwidth 4 GHz and *T_sys* = 20 K, which is $k\,T\,B = 1.38 \times 10^{-23} \times 20 \times 4 \times 10^{9} = 1.10 \times 10^{-12}$ W = –119.6 dBW. Thus the sidelobe-to-sidelobe peak signal is some 37 dB below the system noise in 4 GHz. Thus there is no receiver overloading, even for sidelobes somewhat above 0 dBi. Even precisely on the radar frequency, ALMA would barely detect the signal in this bandwidth.

Class 2: Main beam of the radar to far sidelobes of the ALMA antennas. The main beam gain of the radar antenna is given as 63 dB. The power picked up in the receiving antenna is:

$$(-188.9 + 32.5) + 63 = -93.4 \text{ dBW} = -63.4 \text{ dBm}.$$

Class 3: Sidelobes of the radar into the main beam of an ALMA antenna:

The main beam gain of a 12-m antenna at 94 GHz, assuming 70% aperture efficiency, is 80 dBi. The power picked up by this antenna pointing at 0 dBi sidelobes of the radar transmitting 32.5 dBW is: (–188.9 + 32.5) + 80 = –76.4 dBW = –48.4 dBm.

Compare these main beam-sidelobe and sidelobe-main beam coupling figures calculated in Class 2 and Class 3 with the equivalent thermal noise in a 4 GHz receiver band, at the input to the receiver, of –119.6 dBW, calculated in Class 1 above. In both cases, the received radar power is tens of dB greater than system noise. This is almost certain to cause saturation of the Band 3 ALMA receiver, meaning that useful observations will be impossible, but no physical damage will result. Because of the motion of the satellite (footprint velocity approx 7 km/s), such interactions would last for less than one second for any single antenna, or about 2 s if one considers the 14 km distribution of the large ALMA configuration.

Class 4: Main beam to main beam interaction. From figures used above, the power received is (to the nearest dB) (–188.9 + 32.5) + 63 + 80 = –13 dBW = 17 dBm = 50 mW. This is a harmful level for the receiver.

A burnout figure for an SIS mixer is 1 mW per square micrometer of junction area. This is for DC power, and results from tests that were made a few years ago. Taking details of the 90 GHz mixer into account, it has been calculated that 60 mW of input results in 2 mW per square micrometer, i.e. just a factor of two above the burnout figure. The burnout level for pulsed power would depend on the thermal time constant of the junction, which is not known. The level for the 3.3 μs pulses could be measured, but would not be trivial because a special Dewar setup allowing DC pulses to be injected would be necessary. It was also found that above about 160 GHz, the cut-off of the waveguide at the throat of the feed horn should provide protection from signals at 94 GHz.

Angular avoidance needed between CloudSat and ALMA

1 Receiver damage

ALMA antennas should avoid pointing at the zenith when CloudSat is flying over. From the point of view of receiver survival, what avoidance distance is required between the ALMA antennas and CloudSat’s antenna beam? How close to the zenith is safe?

As shown above, the power received by an ALMA antenna with perfect main beam to main beam coupling is about twice the probable threshold for receiver damage. A slightly conservative goal would be to avoid receiving more than 10% of this threshold. Assuming the worst case of CloudSat flying directly over ALMA, this means that the ALMA antennas should be pointed off the zenith to give at least 13 dB attenuation with respect to their main beam. Sidelobes are assumed to be lower than –13 dB.

– At 94.05 GHz a 12-m dish has a 3 dB beamwidth (full width at half power (FWHP)) of about 0.019°, i.e. ±0.0093°. Assuming a Gaussian beamshape, the –13 dB point will be at ±0.0193°.

– ALMA pointing uncertainty, or definition of “zenith,” should be less than 0.003°.

– A bigger uncertainty is in the potential pointing error of CloudSat; the radar beam may deviate from the local gravitational vector by up to 0.07°, with possible additional pointing error of 0.053°. This gives an extra zenith avoidance margin of 0.053 + 0.07 = 0.123°.

– The satellite radar beamwidth, to first nulls, is ±0.125°.

– Anomalous refraction: in principle, anomalous atmospheric conditions could bend the expected arrival direction of the 94 GHz radar signal by up to 0.01°.

– The ALMA receivers for different bands are all in the same focal plane, with a spread of far field pointing angle of nearly 0.4°.

– Some antennas may have a nutating subreflector, which could move the beam by up to about 0.05°.

– ALMA itself extends over a range of ±0.065° in longitude and latitude, so allowing for ambiguities in whether each local antenna zenith angle is aligned with its own local gravity vector, to be safe we should add this uncertainty to the safety margin.

Adding all these margins (note a direct addition is used, not a quadratic addition) we reach a combined safety margin of ~±0.8°. So, in the worst case even of CloudSat passing directly over ALMA, provided none of the antennas is pointing within 0.8° of the zenith, ALMA should be safe from receiver damage.

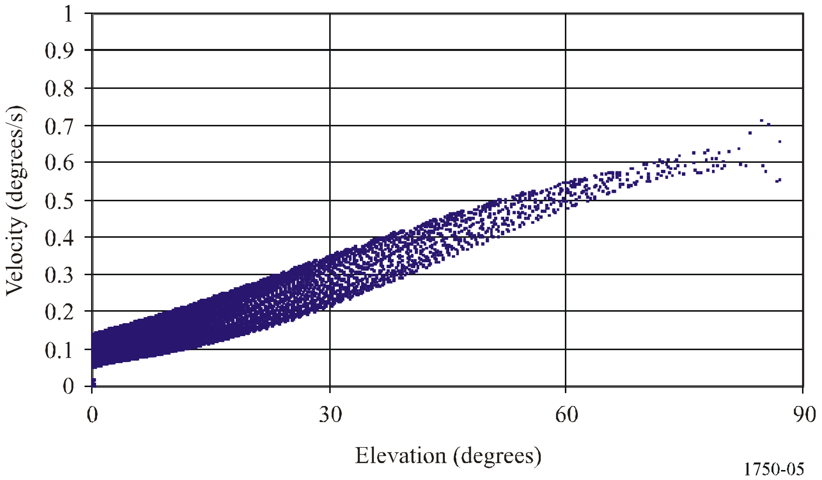
2 Interference

ALMA antennas should avoid pointing at CloudSat at any time when it is above the horizon, in order to avoid excessive interference. How far away from CloudSat is sufficient to reduce interference to tolerable levels?

In the above calculation of power received by an ALMA antenna, with an ALMA antenna main beam looking at CloudSat sidelobes, the received power is –76.4 dBW, with receiver thermal power being –119.6 dBW; i.e. CloudSat is (119.6-76.4) = 43 dB above receiver thermal noise in the assumed bandwidth. Assuming observations are not being attempted within the radar frequency band itself, by analogy with the ITU very long baseline interferometry (VLBI) interference criteria, the total interference power within the receiver band should be kept below 1% of the thermal noise – i.e. below –140 dBW. This requires an attenuation of 43 + 20 = 63 dB, or for the ALMA antenna gain to be reduced from 80 dBi to 17 dBi. From the ITU-R SA.509 model of the envelope of antenna sidelobes, this is expected to occur about 4° from the main beam; however, that antenna model is only intended to be used from 1-30 GHz. From measurements on a 30-m telescope at 39 GHz it is indicated that a safer offset for the 17 dBi gain radius would be 10°. So, in order to avoid excessive interference in the ALMA 90 GHz band, away from the CloudSat frequency, the ALMA antennas should come no closer than ±10° to CloudSat whenever the radar is above the horizon.

FIGURE 5

The range of angular velocities of AQUA/CloudSat seen from ALMA, as a function of satellite elevation angle



This enables the possible duration of interference to be calculated. At elevation angle 30°, if the satellite passes close to the ALMA beam, interference could be expected for a duration of about 70 s.

If observations in the 90 GHz band are in progress when CloudSat passes within 10° of the ALMA field of view, the data should be flagged as suspect. Figure 5 shows the range of satellite angular velocity seen from ALMA (degrees/s), as a function of satellite elevation angle. This enables the likely duration of interference to be calculated for cases where the satellite passes close – i.e. within ±10° – to the ALMA beam. For an overhead satellite pass this period of interference could last up to about 30 s, while for the satellite passing near the ALMA beam at elevation 30°, the interference could last about 70 s, and longer at even lower elevations.

3 Harmonics

The amplitudes of the 2nd and 3rd harmonics (188.1 GHz and 282.15 GHz) of the CloudSat transmitter are unknown but might reasonably be expected to be 50-60 dB below on the fundamental. The e.i.r.p. in the main beam is uncertain: in principle the 2nd harmonic boresight antenna gain could be 6 dB higher, and the 3rd harmonic 10 dB higher, than the fundamental, although it's probably unlikely that the CloudSat antenna will be optimally illuminated at harmonic frequencies – more likely, the residual harmonic energy will be spread out into transmitter sidelobes. Provided that CloudSat is not within ALMA's main antenna beam (or say, within 0.02°), interference from harmonics of CloudSat is only likely to be a problem precisely on the specific harmonic frequencies. The likelihood of ALMA pointing this close to the moving CloudSat in extremely small, and such interference would only be present in any single antenna for less than one second on a given satellite pass. Nevertheless, ALMA's software should probably flag the occurrence.

4 Impact on ALMA

Here are the steps ALMA needs to take in order to avoid a) damage to receivers, and b) data corruption.

– The ALMA antenna should never point within ±0.8° of the zenith. If this is ever necessary, say for maintenance or for transportation, then a protective shutter, or the solar attenuator, should be moved in place above the receiver feeds. If observations are needed within 0.8° of the zenith, then the control software should check for the position of CloudSat before allowing tracking closer to the zenith.

– Whenever ALMA antennas are pointed within 10° of the CloudSat satellite, any data taken at least in the 90 GHz band should automatically be flagged as of questionable value. Harmonic interference is possible if CloudSat passes within 0.02° of the ALMA field of view.

– Observations within the frequency band 94.0-94.1 GHz should preferably be restricted to times when CloudSat is below the horizon.

Conclusions

CloudSat is the first of a series of millimetre-wave radars that may impact ALMA. There is a finite chance of damage to ALMA receivers, which would occur if the radar beam and an ALMA antenna ever look directly at each other with a main beam-to-main beam coupling. However, such an occurrence would be quite rare, and simple precautions can avoid the danger altogether – in particular, if the ALMA antennas are never pointed within 0.8° of their zenith without having receiver protection in place, or without control software first checking whether a CloudSat ground track is likely to pass close to ALMA.

Interference through the far-out sidelobes of the radar beam will be experienced within the 90 GHz band whenever ALMA points within 10° of the satellite; ALMA software should be capable of flagging such circumstances.

For the duration of the lifetime of CloudSat, the ALMA Observatory will require up-to-date orbital elements to enable precise satellite coordinates to be predicted and used by the telescope scheduling, control, and data acquisition software.

Early, and continued, close collaboration between the satellite agency and the RAS is essential in this case, and will be vital for any similar situations in future.