



Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars

Jeffrey J. Plaut,¹ Ali Safaenili,¹ John W. Holt,² Roger J. Phillips,³ James W. Head III,⁴ Roberto Seu,⁵ Nathaniel E. Putzig,³ and Alessandro Frigeri⁶

Received 17 October 2008; revised 4 December 2008; accepted 8 December 2008; published 28 January 2009.

[1] Subsurface radar sounding data indicate that lobate debris aprons found in Deuteronilus Mensae in the mid-northern latitudes of Mars are composed predominantly of water ice. The position in time delay and the relatively low amount of signal loss of the apparent basal reflectors below the debris aprons indicate that aprons contain only a minor component of lithic material. The current presence of large ice masses at these latitudes has important implications for the climate evolution of Mars, and for future targets for in situ exploration. **Citation:** Plaut, J. J., A. Safaenili, J. W. Holt, R. J. Phillips, J. W. Head III, R. Seu, N. E. Putzig, and A. Frigeri (2009), Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars, *Geophys. Res. Lett.*, *36*, L02203, doi:10.1029/2008GL036379.

1. Introduction

[2] Martian surface features identified as lobate debris aprons (LDAs) are thick (100s of m) masses of material that extend up to several 10s of km from high relief slopes and terminate in lobate fronts [Carr and Schaber, 1977; Squyres, 1978, 1979]. Their geomorphic expression and restricted occurrence in latitude has led numerous workers to conclude that LDAs contain water ice, but the suggested amount of ice involved in their formation and evolution has ranged from minor interstitial ice in rocky talus [e.g., Squyres, 1978] to predominantly ice in debris-covered glaciers [e.g., Head et al., 2005; see also Carr and Schaber, 1977; Squyres, 1979; Lucchitta, 1984; Colaprete and Jakosky, 1998; Carr, 2001]. We present new evidence from the Shallow Radar (SHARAD) sounding experiment on Mars Reconnaissance Orbiter (MRO) [Seu et al., 2007] that LDAs in the Deuteronilus Mensae region of the mid-northern latitudes consist mostly of ice.

2. Background

[3] LDAs were first observed in Viking orbiter data, and were interpreted to be members of a class of features

indicative of the presence of ground ice [Carr and Schaber, 1977; Squyres, 1978, 1979]. Deuteronilus Mensae (Figure 1; 40–51°N, 14–35°E), part of the dichotomy boundary “fretted terrain” [Sharp, 1973] contains a high concentration of LDAs [Squyres, 1979; Squyres and Carr, 1986; Hauber et al., 2008] that occur at the bases of scarps of mesas, knobs, craters and valley walls [Chuang and Crown, 2009]. Relief of the adjacent scarps is generally 1–2 km, and most of the LDAs themselves have 300–800 m of relief relative to the surrounding valley floors. LDAs are typically ~10 km wide, measured perpendicular to the trend of the adjacent scarp, with a range of widths of 5–25 km [Li et al., 2005]. Analysis of topographic profiles of LDAs showed them to be consistent with viscous deformation of an ice-rock mixture [Colaprete and Jakosky, 1998; Mangold and Allemand, 2001; Li et al., 2005] but the percentage of ice required to cause flow, and the amount remaining today are uncertain. Ice-assisted creep of talus [Squyres, 1978, 1979] implies less than ~20–30% interstitial and secondary ice, while debris-covered glaciers could be >80% ice covered by a thin debris lag [Colaprete and Jakosky, 1998; Head et al., 2005, 2006a, 2006b], and rock-glacier-like deposits imply intermediate values (30–80%) [Mangold et al., 2002]. Head and Marchant [2006] and Head et al. [2006a, 2006b], analyzed lobate and linear debris aprons (and related lineated valley fill) in the Deuteronilus region and interpreted them as debris-covered remnants of glaciers that formed during the Late Amazonian. Image data show many features indicative of flow and surficial modification likely related to the presence of subsurface ice in the LDAs of this region and in LDAs elsewhere on Mars [e.g., Carr and Schaber, 1977; Squyres, 1978, 1979; Mangold and Allemand, 2001; Mangold, 2003; Pierce and Crown, 2003; Chuang and Crown, 2005; Head et al., 2005, 2006a, 2006b; Chuang and Crown, 2009]. In summary, a range of approaches and analyses suggests that ice is important in the formation of the distinctive shapes, profiles, and textures of LDAs, but the exact amount of ice and its mode of emplacement have been controversial.

3. SHARAD Data

[4] SHARAD is a subsurface radar sounder on MRO operating at a center frequency of 20 MHz [Seu et al., 2007]. Vertical resolution is 15 m in free space, with a horizontal footprint of 0.3–1 km along-track by 2–3 km across-track. Data were processed using a focused synthetic aperture technique. SHARAD has demonstrated the capability to probe through several km of ice-rich polar deposits to detect a lower boundary with a presumably ice-poor substrate [e.g., Phillips et al., 2008]. To date, SHARAD has

¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

²Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA.

³Southwest Research Institute, Boulder, Colorado, USA.

⁴Department of Geological Sciences, Brown University, Providence, Rhode Island, USA.

⁵INFOCOM Department, University of Rome, Rome, Italy.

⁶Dipartimento di Scienze della Terra, Università degli Studi di Perugia, Perugia, Italy.

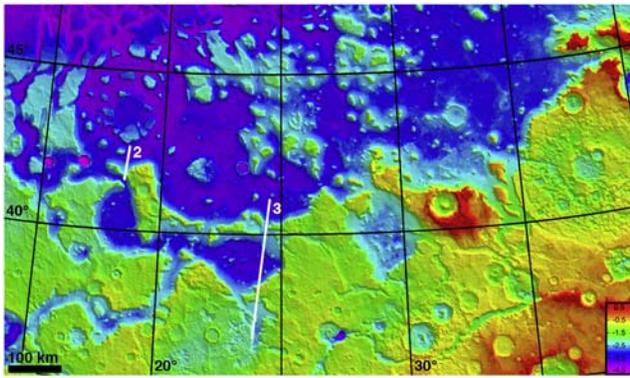


Figure 1. Topographic map of Mars (MOLA data [Smith *et al.*, 2001]) showing the location of Deuteronilus Mensae, centered at 41°N, 26°E. Elevations, in km, are relative to the mean planetary radius. Locations of Figures 2 and 3 are indicated.

acquired observations on more than 100 orbits across the Deuteronilus Mensae LDAs. In SHARAD radargrams, LDAs show a distinctive signature: as the groundtrack proceeds across the valley floor and up the LDA toward the associated scarp, a single surface reflection “splits” into two interfaces at the distal margin of the LDA (Figure 2). The later echo appears at progressively greater time delays indicating an increasing thickness of the deposit. This behavior is essentially identical to that observed at the margin of polar layered deposits in Martian sounding data [Picardi *et al.*, 2005; Plaut *et al.*, 2007]. When the groundtrack reaches the scarp, the later echo abruptly disappears. The complex topography of the fretted terrain frequently generates surface “clutter” signals (energy reflected from off-nadir topographic features) that can appear at time delays similar to subsurface interface detections. To distinguish clutter from subsurface detections, we have generated radargrams of the expected clutter using high-fidelity simulations (Figure 3) employing Mars Orbiter Laser Altimeter (MOLA) gridded topography data [Smith *et al.*, 2001]. Many of the LDAs show late echoes not predicted by the clutter models, making them candidates for subsurface detections. Potential clutter-producing topography may occur at scales smaller than the MOLA grid. However, in most cases, inspection of MOLA topography and higher resolution imagery from the High Resolution Stereo Camera [Neukum *et al.*, 2004] and Thermal Emission Imaging System [Christensen *et al.*, 2004] indicates that surface clutter cannot be responsible for the later echoes, and we thus conclude that SHARAD is detecting subsurface interfaces below the surface of the LDAs.

4. Electrical Properties and Compositional Constraints

[5] We can use SHARAD data to constrain the real and imaginary (loss term) dielectric constant of the LDA material, and thus obtain constraints on their composition. Following the methodology of Watters [2007], we estimate the real part of the dielectric constant (equivalent to the square of the refractive index) by assuming that the detected interface is the continuation of the valley-floor surface

beneath the LDA. In most cases, a real dielectric constant of about 3 (corresponding to pure ice, among other materials) brings the later echo into alignment with the surroundings after a time-to-depth conversion (Figure 3). The sensitivity of this technique can be estimated by varying the assumed value of the real dielectric constant and examining each result for consistency with a flat-lying lower interface. With a real dielectric constant below 3.0, the interface would have to slope downward below the level of the valley floor, which we deem unlikely. With a real dielectric greater than 3.3, the detected interface would have to lie at an intermediate depth within the LDA and again not be coplanar with the valley floor.

[6] We can constrain the loss term by examining the decrease with depth of the echo power from the detected interface. We observe a typical rate of decrease of ~ 2 dB/ μ sec for the two-way echo, equivalent to less than 13 dB/km one-way attenuation for a real dielectric constant of 3. These attenuation values are consistent with relatively pure ice, or a mixture of ice and a lossy contaminant of no more than a few 10s of percent by volume [Heggy *et al.*, 2007]. While ice-free, low-loss materials such as volcanic ash could also

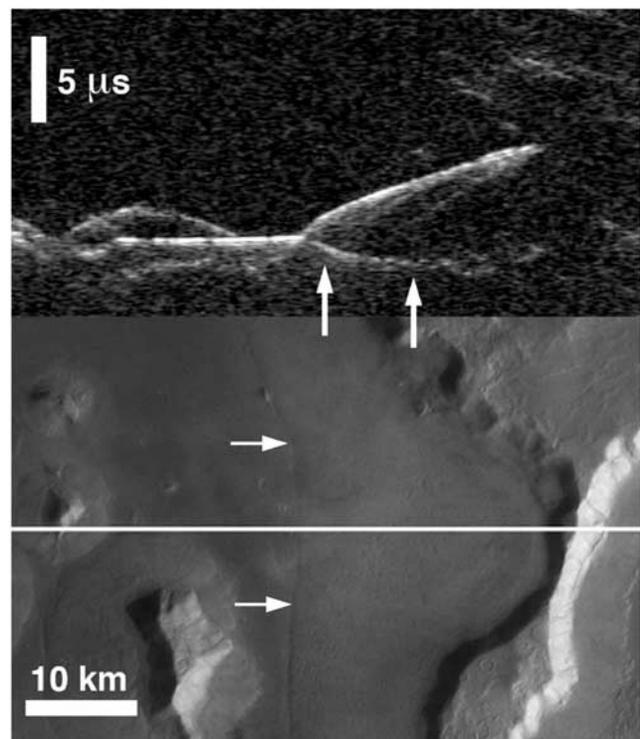


Figure 2. (top) SHARAD radargram and (bottom) High Resolution Stereo Camera [Neukum *et al.*, 2004] image along the groundtrack (white centerline) of lobate debris aprons in Deuteronilus Mensae. Vertical dimension of the radargram is time delay. Arrows in the lower panel indicate the distal margin of the lobate debris apron. Arrows in the upper panel indicate subsurface detections interpreted to be the lower boundary of the apron material. A smaller apron on the left shows echoes from the surface of the apron, the surrounding plain, and the buried base of the apron. SHARAD observation 214501. Center: 42.1°N, 18.5°E. North is to the right.

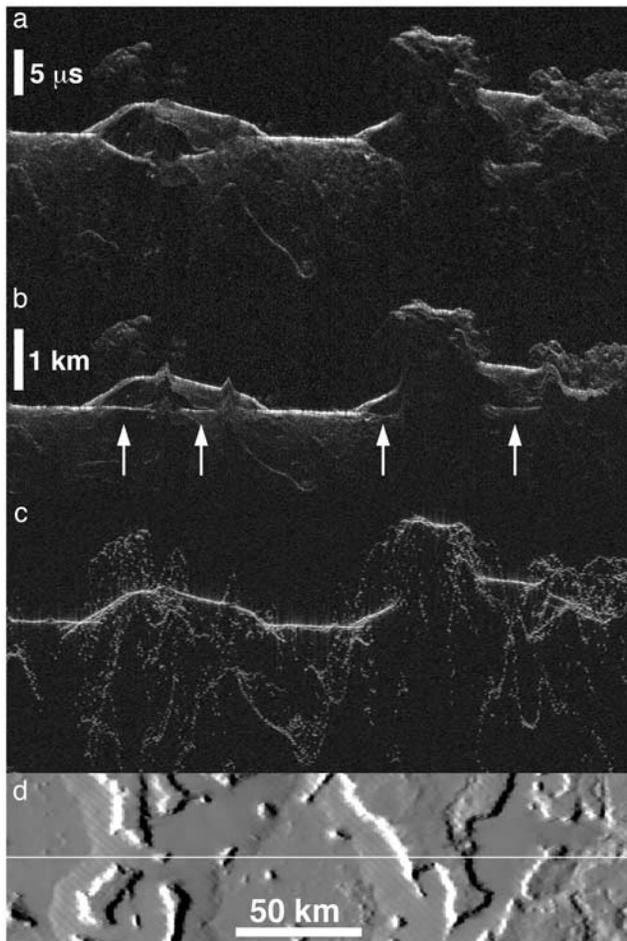


Figure 3. SHARAD radargrams, (a) with the vertical dimension in time delay and (b) with the vertical dimension converted to depth assuming a subsurface dielectric constant of water ice (3.2). Arrows indicate subsurface reflections that are closely coplanar with the adjacent valley floor in the depth-corrected radargram. (c) Simulated radargram showing the expected positions of off-nadir topographic clutter echoes. (d) MOLA topography along the ground track. SHARAD observation 719502. Center: 39.1°N, 24.2°E. North is to the right.

explain these observations (or a mixture of ice and low-loss material), the vast amount of corroborating evidence for ice-rich LDAs in this area from image and topographic data supports an ice-dominated composition. A high fraction of ice in the LDA material is consistent with the hypothesis of *Hauber et al.* [2008], in which moats between mesas and younger lava flows at lower latitudes are the footprints of LDAs that were efficiently removed in response to changing environmental conditions, with the implication that the bulk of the removed LDA material was ice.

5. Implications

[7] The presence of ice at mid-northern latitudes has important implications for the history of water and climate on Mars. The paucity of craters on the LDAs indicates either formation or substantial deformation in mid-to-late

Amazonian time [*Chuang and Crown, 2009*]. LDAs and the associated lineated valley fill have been interpreted as remnants of much larger cold-based glaciers that have been protected from sublimation by a layer of debris shed from neighboring scarps [*Head et al., 2005, 2006a, 2006b; Marchant and Head, 2007*]. Our observations are consistent with this hypothesis; the surficial layer of lithic material in this scenario comprises only a small volumetric fraction of the LDAs, with minimal effects on the electrical properties. The thickness of this layer can be constrained as greater than 0.5 m, based on the lack of a strong hydrogen signature in gamma ray and neutron data [*Boynton et al., 2007; Feldman et al., 2004; Mitrofanov et al., 2002*], and less than ~10 m, based on the lack of a detection of a shallow soil-ice interface in SHARAD data.

[8] Present-day thick ice deposits at the mid-latitudes of Mars should be considered as targets for future landed missions. If accessible, the ice could be analyzed for climatological indicators or biomarkers, and potentially be utilized as a resource. SHARAD data acquired over LDAs in other regions of Mars, including the Eastern Hellas area of the southern hemisphere [*Holt et al., 2008*], show similar signatures of deep penetration and relatively low loss. This spatial distribution implies that these features are not the result of local processes but rather the product of climatic processes operating on a global scale, such as orbitally forced precipitation enhancement, leading to regional glaciation at middle latitudes [*Head et al., 2003*].

[9] **Acknowledgments.** The SHARAD instrument was provided and is operated by the INFOCOM Department of the University of Rome “La Sapienza” and Thales Alenia Space under sponsorship of the Agenzia Spaziale Italiana. MRO is operated by the National Aeronautics and Space Administration’s Jet Propulsion Laboratory and Lockheed Martin Space Systems Company. Part of the research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. J. W. Head is supported under Mars Express HRSC participation, administered by JPL for NASA. We appreciate the reviews by F. Chuang and N. Mangold, who anticipated the value of radar sounding of LDAs [*Mangold, 2003*]. Some figure preparation was done with the “JMARS” tool developed by the Mars Space Flight Facility at Arizona State University.

References

- Boynton, W. V., et al. (2007), Concentration of H, Si, Cl, K, Fe, and Th in the low- and mid-latitude regions of Mars, *J. Geophys. Res.*, *112*, E12S99, doi:10.1029/2007JE002887.
- Carr, M. H. (2001), Mars Global Surveyor observations of Martian fretted terrain, *J. Geophys. Res.*, *106*, 23,571–23,593, doi:10.1029/2000JE001316.
- Carr, M. H., and G. G. Schaber (1977), Martian permafrost features, *J. Geophys. Res.*, *82*, 4039–4054.
- Chuang, F. C., and D. A. Crown (2005), Surface characteristics and degradation history of debris aprons in the Tempe Terra/Mareotis Fossae region, Mars, *Icarus*, *179*, 24–42, doi:10.1016/j.icarus.2005.05.014.
- Chuang, F. C., and D. A. Crown (2009), Geologic map of MTM 35337, 40337, and 45337 quadrangles, Deuteronilus Mensae region of Mars, *U.S. Geol. Surv.*, Flagstaff, Ariz., in press.
- Colaprete, A., and B. M. Jakosky (1998), Ice flow and rock glaciers on Mars, *J. Geophys. Res.*, *103*, 5897–5909, doi:10.1029/97JE03371.
- Christensen, P. R., et al. (2004), Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission, *Space Sci. Rev.*, *110*, 85–130, doi:10.1023/B:SPAC.0000021008.16305.94.
- Feldman, W. C., et al. (2004), Global distribution of near-surface hydrogen on Mars, *J. Geophys. Res.*, *109*, E09006, doi:10.1029/2003JE002160.
- Hauber, E., S. van Gasselt, M. G. Chapman, and G. Neukum (2008), Geomorphic evidence for former lobate debris aprons at low latitudes on Mars: Indicators of the Martian paleoclimate, *J. Geophys. Res.*, *113*, E02007, doi:10.1029/2007JE002897.
- Head, J. W., and D. R. Marchant (2006), Evidence for global-scale northern mid-latitude glaciation in the Amazonian period of Mars: Debris-covered

- glacier and valley glacier deposits in the 30°–50°N latitude band, *Proc. Lunar Planet. Sci. Conf.*, 37th, Abstract 1127.
- Head, J. W., et al. (2003), Recent ice ages on Mars, *Nature*, 426, 797–802, doi:10.1038/nature02114.
- Head, J. W., et al. (2005), Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars, *Nature*, 434, 346–351, doi:10.1038/nature03359.
- Head, J. W., A. L. Nahm, D. R. Marchant, and G. Neukum (2006a), Modification of the dichotomy boundary on Mars by Amazonian mid-latitude regional glaciation, *Geophys. Res. Lett.*, 33, L08S03, doi:10.1029/2005GL024360.
- Head, J. W., et al. (2006b), Extensive valley glacier deposits in the northern mid-latitudes of Mars: Evidence for Late Amazonian obliquity-driven climate change, *Earth Planet. Sci. Lett.*, 241, doi:10.1016/j.epsl.2005.11.016.
- Heggy, E., et al. (2007), On the dielectric properties of dust and ice-dust mixtures: Experimental characterization of the Martian polar layered deposits analog materials, *Proc. Lunar Planet. Sci. Conf.*, 38th, Abstract 1756.
- Holt, J. W., et al. (2008), Radar sounding evidence for buried glaciers in the southern mid-latitudes of Mars, *Science*, 322, 1235–1238, doi:10.1126/science.1164246.
- Li, H., M. S. Robinson, and D. M. Jurdy (2005), Origin of Martian northern hemisphere mid-latitude lobate debris aprons, *Icarus*, 176, 382–394, doi:10.1016/j.icarus.2005.02.011.
- Lucchitta, B. K. (1984), Ice and debris in the fretted terrain, Mars, *J. Geophys. Res.*, 89, B409–B418, doi:10.1029/JB089iS02p0B409.
- Mangold, N. (2003), Geomorphic analysis of lobate debris aprons on Mars at Mars Orbiter Camera scale: Evidence for ice sublimation initiated by fractures, *J. Geophys. Res.*, 108(E4), 8021, doi:10.1029/2002JE001885.
- Mangold, N., and P. Allemand (2001), Topographic analysis of features related to ice on Mars, *Geophys. Res. Lett.*, 28, 407–410, doi:10.1029/2000GL008491.
- Mangold, N., P. Allemand, P. Duval, Y. Géraud, and P. G. Thomas (2002), Experimental and theoretical deformation of ice–rock mixtures: Implications on rheology and ice content of Martian permafrost, *Planet. Space Sci.*, 50, 385–401, doi:10.1016/S0032-0633(02)00005-3.
- Marchant, D. R., and J. W. Head III (2007), Antarctic dry valleys: Microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars, *Icarus*, 192, 187–222, doi:10.1016/j.icarus.2007.06.018.
- Mitrofanov, I., et al. (2002), Maps of subsurface hydrogen from the High Energy Neutron Detector, Mars Odyssey, *Science*, 297, 78–81, doi:10.1126/science.1084350.
- Neukum, G., R. Jaumann, and HRSC Co-Investigator and Experiment Team (2004), HRSC: The High Resolution Stereo camera of Mars Express, in *Mars Express—The Scientific Payload*, Eur. Space Agency Spec. Publ., ESA SP-1240, pp. 17–35.
- Phillips, R. J., et al. (2008), Mars north polar deposits: Stratigraphy, age, and geodynamical response, *Science*, 320, 1182–1185, doi:10.1126/science.1157546.
- Picardi, G., et al. (2005), Radar soundings of the subsurface of Mars, *Science*, 310, 1925, doi:10.1126/science.1122165.
- Pierce, T. L., and D. A. Crown (2003), Morphologic and topographic analyses of debris aprons in the eastern Hellas region, Mars, *Icarus*, 163, 46–65, doi:10.1016/S0019-1035(03)00046-0.
- Plaut, J. J., et al. (2007), Subsurface radar sounding of the south polar layered deposits of Mars, *Science*, 316, 92–95, doi:10.1126/science.1139672.
- Seu, R., et al. (2007), SHARAD sounding radar on the Mars Reconnaissance Orbiter, *J. Geophys. Res.*, 112, E05S05, doi:10.1029/2006JE002745.
- Sharp, R. P., et al. (1973), Mars: Fretted and chaotic terrain, *J. Geophys. Res.*, 78, 4073–4083, doi:10.1029/JB078i020p04073.
- Smith, D. E., et al. (2001), Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars, *J. Geophys. Res.*, 106(E10), 23,689–23,722, doi:10.1029/2000JE001364.
- Squyres, S. W. (1978), Martian fretted terrain: Flow of erosional debris, *Icarus*, 34, 600–613, doi:10.1016/0019-1035(78)90048-9.
- Squyres, S. W. (1979), The distribution of lobate debris aprons and similar flows on Mars, *J. Geophys. Res.*, 84, 8087–8096, doi:10.1029/JB084iB14p08087.
- Squyres, S. W., and M. H. Carr (1986), Geomorphic evidence for the distribution of ground ice on Mars, *Science*, 231, 249–253, doi:10.1126/science.231.4735.249.
- Watters, T. R. (2007), Radar sounding of the Medusae Fossae Formation Mars: Equatorial ice or dry, low-density deposits?, *Science*, 318, 1125–1128, doi:10.1126/science.1148112.
- A. Frigeri, Dipartimento di Scienze della Terra, Università degli Studi di Perugia, I-06123 Perugia, Italy.
- J. W. Head III, Department of Geological Sciences, Brown University, Box 1846, Providence, RI 02912, USA.
- J. W. Holt, Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, TX 78758, USA.
- R. J. Phillips and N. E. Putzig, Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, USA.
- J. J. Plaut and A. Safaeinili, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA. (plaut@jpl.nasa.gov)
- R. Seu, INFOCOM Department, University of Rome, I-00184 Rome, Italy.